THE DIELS–ALDER DIENE SYNTHESIS

JAMES A. NORTON

Chemical Research Division, Electrochemicals Department, E. I. du Pont de Nemours & Co., Inc., Niagara Falls, New York

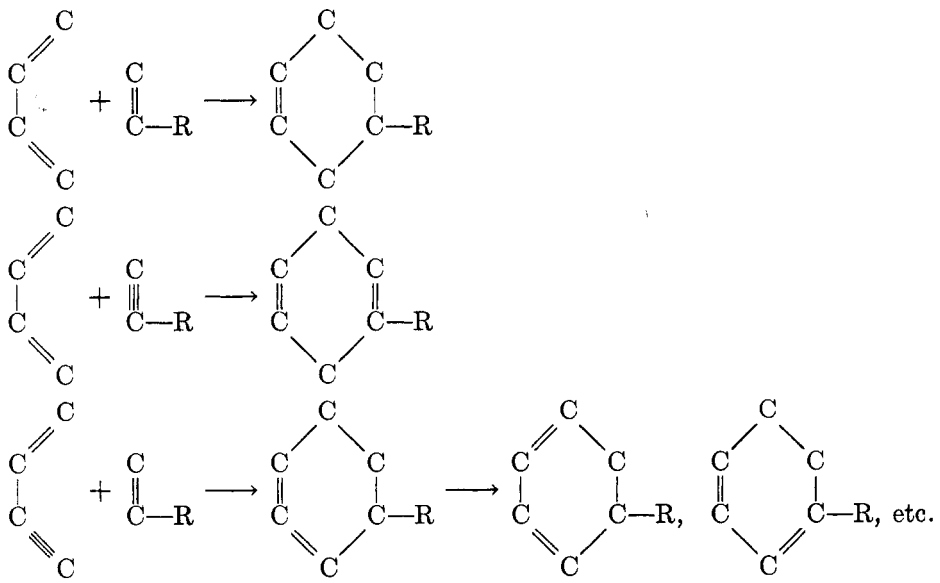
Received January 22, 1942
Revised August 19, 1942

CONTENTS

I. INTRODUCTION

A. Definition

The diene synthesis (often termed the Diels–Alder reaction or the Diels–Alder diene synthesis) is more than the name implies. Enynes and diacetylenes may also undergo typical diene synthesis reactions. Basically, the great majority of these syntheses may be classified under one of the following types:



R in the above examples is usually of the types which terminate in a carbonyl group attached directly to one of the olefinic or acetylenic carbon atoms. Repre-

sentative dienophiles of this type are acids, their anhydrides, esters, and halides, and also aldehydes, ketones, or quinones. The carbonyl group is not a necessary structural feature, however. It will be shown later that R may be acetoxyl (as in vinyl acetate), nitro, sulfonyl, cyano, amino, vinyl, or even hydrogen. Diene syntheses proceed with greatest facility, however, when R contains the carbonyl group in the manner indicated above.

B. Nomenclature

The compound which acts in the capacity of C=C—R or C≡C—R is designated as the *philodiene* or *dienophile*; the latter term seems less confusing. The etymology of these terms from the Greek is apparent. The other compound involved in the reaction, whether it be diene, polyene, enyne, or diyne, will be referred to as the *diene* in this review purely for the sake of convenience. The reaction product is the *adduct* or *adject*. The *diene* and *dienophile* are often designated collectively by the term *generators*.

C. Dienes

The forms which the diene may assume are amazingly variable. For instance, the diene may be simple, as piperylene or isoprene; or it may be more complex, as furan, pyrrole, thebaine, tetraphenylcyclopentadienone, pyridine, anthracene, ergosterol, cycloheptadiene, α-naphthylacetylene, 3,4-dihydro-1-vinylnaphthalene, 1,3-menthadiene, or 1,2,5,6-dibenzanthracene. Neither thionessal (tetraphenylthiophene) nor thiophene itself has been observed to add dienophiles, and the same is probably true of the thiotolenes, thioxenes, and selenophene. The whole subject of non-addition of dienophiles by thiophene and its derivatives has, however, been reopened by Clapp's discovery (400) that one compound of this series will add dienophiles at temperatures in the neighborhood of those employed for sulfur dehydrogenation of hydroaromatic compounds. In the investigations of the other thiophene compounds it is doubtful that the temperatures used by Clapp were employed. Clapp's reaction occurs with the evolution of hydrogen sulfide as in a sulfur dehydrogenation, and it may be that other thiophenes will respond under similar conditions.

Benzene and its simpler derivatives have been observed not to add dienophiles. Compounds do exist, however, in which one of the diene double bonds is a Kekulé double bond. Anethole and α-phenylstyrene are compounds of this type; they add maleic anhydride with reduction of one of the benzene rings to a cyclohexadiene ring. α-Vinylnaphthalene acts in a similar manner. One example (9,10-anthraquinone) appears to be known in which a lone benzene ring is able to add dienophiles, but this is disputed by a negation published prior to the above report. Heterocyclic dienes containing nitrogen as a part of the ring (pyrrole or pyridine) invariably react abnormally. Elsewhere the diene synthesis usually gives products the formulas of which are in accordance with the general statement of the synthesis as given by the reaction types on page 320. It is occasionally found that certain compounds containing isolated double bonds, one double bond, or even no double bonds at all will add dienophiles.

This phenomenon usually can be explained by assumption of a preliminary isomerization or conversion of the compound in question to another substance containing isolated double bonds, and eventually to one containing conjugated double bonds which is able to add the dienophile. Such examples are found almost exclusively among the terpinoids.

Occasionally the adduct will decompose in a predictable manner when heated, or upon formation if the temperature of the reaction mixture of diene and dienophile is sufficiently high. Adducts of acetylenic dienophiles with cyclohexadienes, cyclopentadienones, and derivatives of the lactone of 1-hydroxy-4-carboxy-1,3-butadiene (cumalin) evolve ethylenes, carbon monoxide, and carbon dioxide, respectively, when pyrolyzed.

Only a limited number of enynes has been studied. Butz has done most of the existing work in this field which, though not well developed, offers considerable promise.

At least one phase of the well-known trimerization of acetylene to benzene might be regarded as a diene synthesis. This phase would be the addition of a mole of acetylene to the dimer of acetylene (vinylacetylene), yielding benzene. It should be said that there is apparently no conclusive proof that the trimerization proceeds through such a mechanism; but since no proof of any other definite mechanism appears to have been established, the author feels that the mechanism of the diene synthesis for the formation of benzene is as admissible for consideration as any other mechanism.

D. Allenes

Dienes containing the grouping C=C=C do not react directly with dienophiles. Reaction is possible through the mechanism of an initial isomerization to a conjugated system, such as could occur at elevated temperatures. A few allenes have been studied; thus, 1-cyclohexyl-2,3-pentadiene (2) was found not to react with maleic anhydride (see also 403, 404).

E. Tests for dienes

Since a transient yellow color is observed in the reaction of maleic anhydride with dienes, it had been proposed that the appearance of such a color on treatment of an unknown substance with maleic anhydride was a positive test for a conjugated dienoid system. Sandermann (323, 324) found that the test was unreliable, since positive results were secured with resorcinol, hydroquinone, pyrocatechol, benzidine, diethylaniline, diphenylamine, brucine, anethole, and carbazole, as well as with ergosterol, α-phellandrene, abietic acid, isoeugenol, anthracene, and pyrene. Apparently a negative test is of more value than a positive test.

The Fieser test (203) for conjugated dienes consists in treating the unknown with a solution of diazotized *p*-nitroaniline. If an orange color develops within a reasonable time, the test is positive. Arbuzov and Rafikov (60) believe the test to be unreliable, for in the reaction of dienes with the Fieser reagent some dinitrodiazobenzene is always formed. The structure of the coupling product

with butadiene (60) is probably *p*-nitrobenzeneazo-1-butadiene, for reduction gives *p*-phenylenediamine and pyrroline. Goodway and West (229) obtained positive tests using caryophyllene, α- and β-phellandrenes, α-pinene, 3-carene, and dipentene. Save for the phellandrenes, not one of these compounds contains a conjugated system.

F. trans-Butadienoid systems

The Bredt addition rule (322, 324) postulates that in cyclic dienes, the two double bonds must be in the same ring in order that addition of dienophiles may occur according to the diene synthesis. In contradiction to this rule, it is found that bis-1-dialin (3,4,3′,4′-bis(dihydro-α-naphthyl)) adds dienophiles without double-bond wandering prior to addition; and many other similar examples may be found, such as the addition of dienophiles by 2,3,4,5,2′,3′,4′,5′-octahydrobiphenyl. The rule should be modified by stating that the two double bonds of the conjugated system must be in the *cis*-configuration with each other or else must rearrange to such a configuration before addition can occur. In the majority of cases free rotation of the single bond between the 2- and 3-carbon atoms of the butadienoid portion of the molecule makes assumption of either a *cis*- or a *trans*-configuration a simple matter. In certain cases, however, only a *trans*-butadienoid system may exist without placing a large amount of strain on the molecule. The *trans*-butadienoid systems of β-phellandrene and 3,5-cholestadiene (cholesterilene) cannot well change into *cis*-butadienoid systems without double-bond migration. Addition to these molecules proceeds with great difficulty and probably with rearrangement and polymerization. Thus, β-phellandrene and maleic anhydride give tars and a small yield of the adduct of α-phellandrene and maleic anhydride. The adduct is obtainable only on vacuum distillation of the tar (228). Cholesterilene (332) adds maleic anhydride (348) only under drastic conditions to give a product the alkali salts of which are insoluble in water (distinction from other sterol–maleic anhydride adducts), and which are probably polymeric. Certain other sterol dienes of *trans*-butadienoidal configuration have been shown not to react with maleic anhydride (405).

II. DISCOVERY OF THE DIENE SYNTHESIS

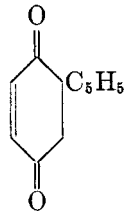
Isolated examples of the diene synthesis appear in the literature of the past half-century, but the extensive development of the subject did not begin until 1928, when Diels and Alder recognized that a reaction observed by Euler and Josephson (195) between *p*-benzoquinone and isoprene was strikingly similar to a reaction—observed by Diels, Blom, and Koll (157)—of azodicarboxylic ester with cyclopentadiene and also with isoprene derivatives. That the reaction was possibly of general application can be sensed from the paper of Diels, Blom, and Koll, and apparently the years 1925–1928 were devoted to experimentation designed to show that such actually was the case.

An early series of papers by Zincke and coworkers (376–378) dealt with the reactions of 1,2,4,5,5-pentachlorocyclopenten-3-one. Loss of a molecule of

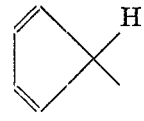
hydrogen chloride from this compound gave tetrachlorocyclopentadienone. Since this compound contains the structures of reactive diene and reactive dienophile, it was not isolated as such, but rather as the dimer which was formed according to the Diels–Alder diene synthesis. The dimer was an intermediate product in a series of reactions ending in octachlorohydrindone, which was easily reduced to hexachloroindone.

Staudinger (337) has made a very famous series of researches on polymerization and on compounds of high molecular weight. It was his opinion that the dimerization of cyclopentadiene occurred to give compounds containing cyclobutane rings. The dimer of cyclopentadiene was considered to be the product of the 1,2-addition of two molecules of monomer to each other. The structure of such a product would be that of a cyclobutane with two cyclopentene rings fused to it. In a brilliant series of papers on the structure of cyclopentadiene polymers, Alder and Stein showed that these were formed by the 1,4-addition of a molecule of cyclopentadiene to a double bond of cyclopentadiene monomer or polymer. The structure of cyclopentadiene dimer (dicyclopentadiene) is that of a partially hydrogenated indene possessing a methylene bridge across the 4- and 7-positions. 1,4-Addition of cyclopentadiene to this compound occurs at the double bond of the six-membered ring, giving cyclopentadiene trimer. In the production of higher polymers, 1,4-addition of cyclopentadiene to its polymer always occurs at the double bond of the terminal six-membered ring and never at the double bond of the five-membered ring.

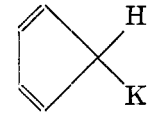
Albrecht (379) described, in 1906, certain experiments in which cyclopentadiene was caused to react with quinones and ketones. The reaction product of *p*-benzoquinone with an equimolecular quantity of cyclopentadiene was thought to be I. While the structure of the C_5H_5 group was not stated explicitly,



I



II



III

it probably was intended to be as shown in formula II, for cyclopentadiene forms a potassium derivative (III).

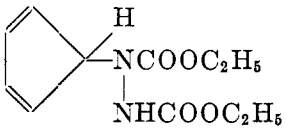
Albrecht was not altogether certain of the validity of structure I for his product. He also found that a second mole of cyclopentadiene would react with *p*-benzoquinone; the structure assigned to this product was that of 2,5-bis-cyclopentadienyl-tetrahydro-*p*-benzoquinone, although he recognized the possibility of 2,6 and 2,3 isomerism. Other quinones, such as chloranil and 1,4-naphthoquinone, were shown to react. A period of 2 hr. was required for the reaction of *p*-benzoquinone with a benzene solution of cyclopentadiene at

0°C., while chloranil required two weeks; both chloranil and 1,4-naphthoquinone would react with only 1 mole of the diene. 9,10-Anthraquinone, 9,10-phenanthrenequinone, β-naphthoquinone, benzil, benzalacetone, dibenzalacetone, phorone, and dibenzoylstyrene would not react under the mild conditions used. Since that time it has been found that β-naphthoquinone and the unsaturated ketones will react at higher temperatures.

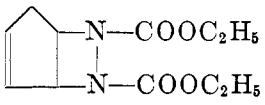
Staudinger's work suggested that the condensation product of cyclopentadiene with *p*-benzoquinone was analogous to the dimer obtained from cyclopentadiene, for the structure he assigned to the condensation product was that of a compound formed by addition of cyclopentadiene and *p*-benzoquinone by the 1,2-addition mechanism.

In 1920, Euler and Josephson (195) published the paper already referred to, which concerned the reaction of isoprene with *p*-benzoquinone. The product obtained was assigned the structure of 2,6-dimethyl-1,4,5,8,1a,4a,5a,8a-octahydro-9,10-anthraquinone. This structure was nearly correct, for it was shown later (153) that the product was really a mixture of the 2,6- and 2,7-dimethyl-1,4,5,8,1a,4a,5a,8a-octahydro-9,10-anthraquinones.

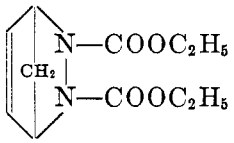
The paper of Diels, Blom, and Koll (157) was next to appear. They paid particular attention to the structure of the reaction product that was obtained from cyclopentadiene and azodicarboxylic ester. In accordance with the assumptions of Albrecht, the structure of the product was first given as shown in formula IV. The assumptions of Staudinger led to formulation of the struc-



IV

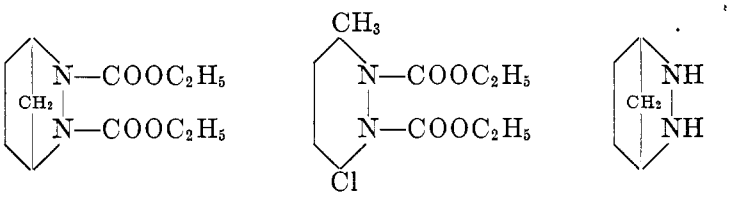


V



VI

ture as V, while the work of Euler and Josephson led to formulation of the structure as VI. Since the adduct took up only two atoms of hydrogen or bromine, structure IV was invalidated. Confirmation of formula VI was secured in several ways. First, the methylene bridge of the hydrogenated adduct (VII) was broken with hydrogen chloride to give a methylchloropiperidazine derivative (VIII). Secondly, the same hydrogenated adduct was saponified and decarboxylated to give an endomethylenepiperidazine (IX), vigorous reduction of which gave 1,3-diaminocyclopentane. No such compound could have been obtained from either compound IV or compound V.



VII VIII IX

These facts threw grave doubts upon the Albrecht structure for the adducts of cyclopentadiene and *p*-benzoquinone, and furnished the initiative for the beginning of a program of research marked by the appearance of the first epochal paper by Diels and Alder (136). It should be noted that a considerable number of patents on the additions of dienes and dienophiles were taken out almost simultaneously by the I. G. Farbenindustrie A.-G.

In their first paper on diene syntheses, Diels and Alder presented evidence in support of their belief that Albrecht's addition compound between cyclopentadiene and α-naphthoquinone was 1,1a,4,4a-tetrahydro-1,4-endomethylene-9,10-anthraquinone, since the corresponding adduct between α-naphthoquinone and butadiene was easily oxidized to anthraquinone. Later (146) they were able to convert the cyclopentadiene adduct itself to anthraquinone, thus meeting the objections of Staudinger who insisted that the adduct was formed by 1,2-addition of cyclopentadiene to the quinone ring of α-naphthoquinone. The views of Diels and Alder concerning the structures of their products were the subjects of intense criticism at first, for it was thought that these might conceivably be "molecular compounds" somewhat akin to the compounds of the polynuclear hydrocarbons with picric acid, 1,3,5-trinitrobenzene, and styphnic acid. This view received apparent substantiation by the discovery that certain of the adducts would decompose into their generators on distillation. However, the formation of derivatives of anthracene could not be explained by the view which assumed that the adducts were so-called molecular compounds, and eventually the differing stabilities of individual adducts were made use of in the first preparation of the acid chloride of acetylenedicarboxylic acid (172) and in other ingenious, convenient, and useful syntheses.

The study of the diene synthesis has been pursued intensively since the publication of the initial papers of Diels and Alder. It is a matter of some difficulty to find a volume of a chemical journal of today which does not contain an article which bears on some phase of the diene synthesis. Today one sees polyesters the acid fractions of which are prepared by the diene reaction between abietic acid and maleic anhydride (304). By offering means for the quantitative determination of conjugated dienes in petroleum products, the diene reaction will facilitate the perfection of processes which produce motor fuels of initially high octane ratings and high lead susceptibilities combined with improved stabilities. The number of possible practical applications of the general principle of the diene synthesis is virtually unlimited.

III. DIENOPHILES

The types of compounds which may be used as dienophiles will be considered initially, for the majority of studies in the field of the diene synthesis were based primarily on the determination of the capacity of the compound under investigation to act as a diene in the diene synthesis. Since a considerable amount of work has been conducted with regard to quinones in the diene synthesis, these dienophiles will be discussed in the section to follow.

The types of dienophilic compounds which may be employed in the diene synthesis are nearly as diverse in character as the types of compounds which may serve as dienes. They may be added to the reaction mixture as such, or prepared *in situ* (47, 239).

A. Olefinic dienophiles

As stated previously, the dienophiles which add most readily are those containing the groupings C=C—C=O or C≡C—C=O, and these have been the most extensively studied of dienophilic substances. With them, many diene syntheses occur readily at room temperature to give nearly quantitative yields of adducts. Examples of such dienophiles are crotonaldehyde, acrolein, 3,4-diketo-1-pentene, *sym*-dibenzoylethylene, 1-cyclopenten-3-one, acrylic acid, methyl acrylate, fumaroyl chloride, maleic anhydride, tetrolic acid, propiolic ester, acetylenedicarboxylic ester, *p*-benzoquinone, α-naphthoquinone, and *p*-toluquinone. With the exception of the nitrogen heterocycles, additions almost always occur in the manner indicated by the general rule for diene reactions as given on page 320. Thus, acrolein reacts with butadiene to give Δ^3-tetrahydrobenzaldehyde, and α-naphthoquinone and butadiene give 1,4,1a,4a-tetrahydro-9,10-anthraquinone (136). The nature of the solvent has no effect on the composition of the product, but ordinarily (196) reaction occurs about five times as rapidly in a polar solvent (ethanol) as it does in a non-polar solvent such as benzene.

Substituents located on the atoms of the carbon-to-carbon double bond (the "carbonylenic" (106) double bond) of the C=C—C=O group definitely decrease dienophilic character. Two exceptions to this rule are the carbonyl group (as shown by the dienophilic property of ethylenetetracarboxylic ester) and groups which may split off easily during the course or after the completion of the diene synthesis (these are notably hydroxyl and the halogens). All other substituents, with the possible exception of the cyano group, tend to decrease the dienophilic property of the carbonylenic double bond.

The extent to which these substituents suppress dienophilic property depends to a great extent on the type of dienophile. These may be roughly divided into four classes:

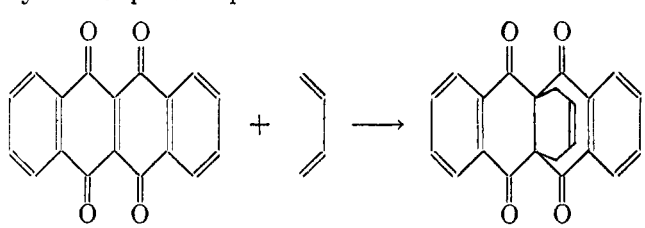
Class A: Alkyl and aryl derivatives of acrolein, maleic anhydride, acrylic acid, and methyl or other alkyl or aryl vinyl ketones. These include such compounds as cinchonic anhydride, cinnamic acid, benzalacetophenone, crotonaldehyde, etc. The decrease of dienophilic activity is not of great magnitude, and is usually manifested only in cases of dienes of low reactivity or which have

groups on the 1- and 4-positions of the butadienoid system, when addition either is slow or fails to occur.

Class B: Fused-ring derivatives of acrolein, maleic anhydride, acrylic acid, and vinyl ketones. These include the adducts of equimolar quantities of diene and α,β-acetylenic acids and, generally speaking, all cyclene aldehydes, acids, and their derivatives, as well as cyclic ketones such as cyclopenten-3-one. Increase in unsaturation of the fused ring other than that of the carbonylenic group results in diminishing dienophilic properties. Thus, cyclohexene-1,2-dicarboxylic anhydride and 1,4-cyclohexadiene-1,2-dicarboxylic anhydride add butadiene with considerably greater difficulty than does maleic anhydride, while 1,3,5-cyclohexatriene-1,2-dicarboxylic anhydride (phthalic anhydride) has never been observed to add any dienes whatsoever.

Class C: Alkyl- or aryl-substituted quinones. Alkyl or aryl substituents of *p*-benzoquinone suppress the dienophilic activity of the carbonylenic group to which they are attached, but have little or no effect on the activity of the other carbonylenic group. Thus, *p*-toluquinone adds butadiene readily to give an adduct which does not possess an angular methyl group. This primary product of addition will add a second mole of butadiene to give an octahydroanthraquinone possessing an angular methyl group, but the addition takes place only with considerable difficulty.

Class D: Quinones with fused rings. These resemble Class B dienophiles. Thus, 1,4,5,8-tetrahydroanthraquinone will add dienes with considerable difficulty, and anthraquinone and phenanthrenequinone add no dienes whatsoever. However, fusion of two quinone rings to each other is actually the substitution of —CO— groups on a carbonylenic double bond, and therefore dienophilic activity is not suppressed. Naphthacenediquinone adds dienes almost as readily as does *p*-benzoquinone:



Naphthacenediquinone

To generalize broadly, it may be said that dienes and dienophiles will tend to react, as far as possible, to give adducts which do not possess angular, geminal, or spirane groupings on the carbon atoms which formerly were the carbon atoms of the carbonylenic double bond.

B. Acetylenic dienophiles

The above steric hindrance factors apply but little to the acetylenic dienophiles, since angular, geminal, or spirane groupings are not formed when these

substances add dienes. Addition to eneynes will give benzene derivatives directly, while addition of these dienophiles to diynes has not been attempted. The structure of the product from such a reaction, if reaction occurs, is indeed a matter for conjecture. Certain acetylenic derivatives, including acetylene itself, have been added to highly reactive dienes such as phencyclone (1,4-diphenyl-2,3-(*o*,*o*′-biphenylene)cyclopentadienone), but the most thoroughly studied derivatives have been those possessing *carbonylynic* groups, such as propiolic acid, acetylenedicarboxylic acid, and their methyl and ethyl esters. The adducts derived from the interaction of equimolecular quantites of acetylenic dienophile and *true* diene possess the carbonylenic grouping (if derived from the acetylenic acids) and are potentially able to add a second mole of diene. These primary adducts are dienophiles of Class B (see page 328) and are subject to the limitations of reaction rates of that class. The fact that these primary adducts may be isolated, usually in good yields, indicates that the second mole of diene is added with considerably greater difficulty than the first. This is reminiscent of the increasing difficulty in the progressive introduction of nitro groups into the aromatic nucleus.

It will be noted that the aliphatic dienophiles which add dienes readily are of the same type as those which add ammonia, amines, and hydrogen cyanide with ease.

C. Non-carbonylenic dienophiles

Dienophiles which possess neither the carbonylenic nor the carbonylynic group usually require elevated temperatures and occasionally an antioxidant (hydroquinone) to minimize polymerization of the diene. Temperatures as high as 200°C. may be required, but dienophiles with strongly acid groups attached to the carbon atoms of the double bond do not require conditions which are quite that drastic.

Dimerization of dienes forms a special case wherein the diene acts as its own dienophile. This is perhaps the earliest known type of diene synthesis, and sufficient study has been made of the subject to warrant its being treated separately.

Table 1 summarizes the work accomplished with the addition of non-carbonylenic dienophiles to dienes. It will be noted that β-naphthol is capable of adding dienes, since its keto tautomer possesses the carbonylenic group.

Referring to table 1, it will be seen that secondary addition of cyclopentadiene to the normal adduct occurred in a number of cases, particularly those in which the reaction temperatures were higher than 100–110°C. Since the primary adducts are non-carbonylenic dienophiles, and since cyclopentadiene is a particularly reactive diene, addition to form secondary products is not surprising. The fact that considerable amounts of such products are formed indicates that the dienophilic activity of the dienophile employed in any one of these reactions is not much greater than that of the primary adduct with cyclopentadiene.

TABLE 1

Diene additions of non-carbonylenic dienophiles

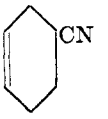
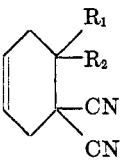
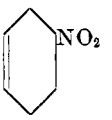
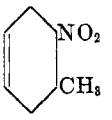
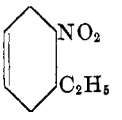
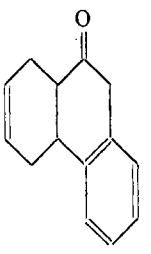
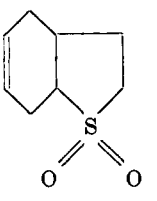
DIENE	DIENOPHILE	TEMPERATURE	PRODUCT	REFERENCE
Butadiene.....	Acrylonitrile	°C.		(371)
Butadiene, isoprene.	Methylene-malononitrile derivatives			(382)
Butadiene.....	Nitroethylene	100–110		(20)
Butadiene.....	1-Nitro-1-propene	100–110		(20)
Butadiene.....	1-Nitro-1-butene	100–110		(20)
Butadiene.....	β-Naphthol			(321)
Butadiene.....	Dihydrothiophene dioxide	100–110		(20)

TABLE 1—*Continued*

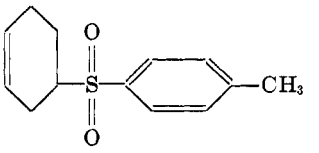
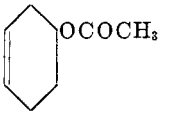
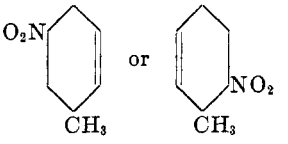
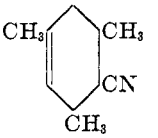
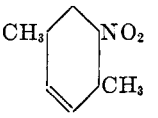
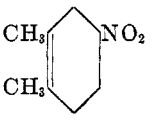
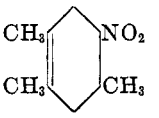
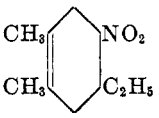
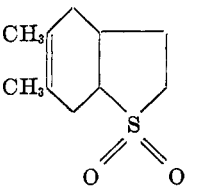
DIENE	DIENOPHILE	TEMPERATURE	PRODUCT	REFERENCE
		°C.		
Butadiene.....	Vinyl-*p*-tolyl sulfone	100–110		(20)
Butadiene*.....	Vinyl acetate	180		(19)
Piperylene	Nitroethylene	100–110		(20)
1,3-Dimethylbutadiene.....	Crotononitrile			(246)
1,4-Dimethylbutadiene.....	Nitroethylene	100–110		(20)
2,3-Dimethylbutadiene.....	Nitroethylene	100–110		(20)
2,3-Dimethylbutadiene.....	1-Nitro-1-propene	100–110		(20)
2,3-Dimethylbutadiene.....	1-Nitro-1-butene	100–110		(20)
2,3-Dimethylbutadiene.....	Dihydrothiophene dioxide	100–110		(20)

TABLE 1—*Continued*

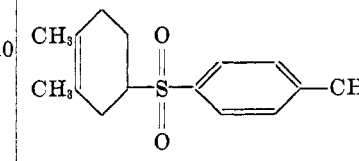
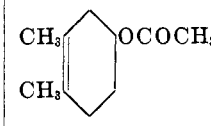
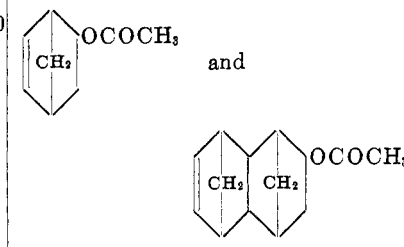
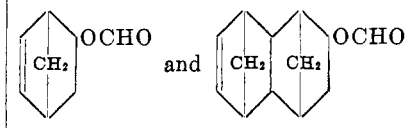
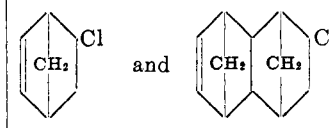
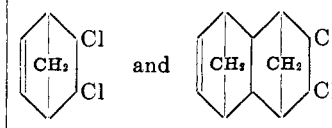
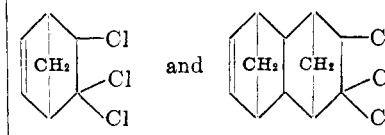
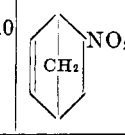
DIENE	DIENOPHILE	TEMPERATURE	PRODUCT	REFERENCE
		°C.		
2,3-Dimethylbutadiene	Vinyl-*p*-tolyl sulfone	100–110		(20)
2,3-Dimethylbutadiene	Vinyl acetate	180		(19)
Cyclopentadiene†	Vinyl acetate	185–190		(19)
Cyclopentadiene†	Vinyl formate	180		(19)
Cyclopentadiene†	Vinyl chloride	185		(19)
Cyclopentadiene†	1,2-Dichloroethylene	185		(19)
Cyclopentadiene†	Trichloroethylene	185		(19)
Cyclopentadiene‡	Nitroethylene	100–110		(20)

TABLE 1—*Continued*

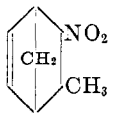
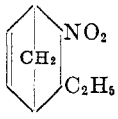
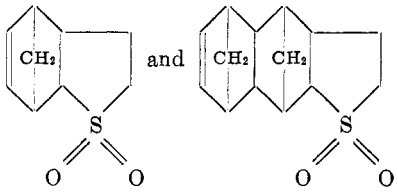
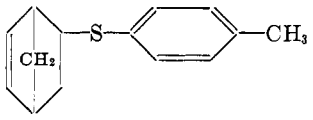
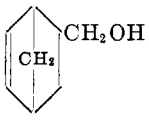
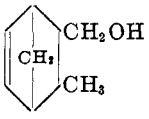
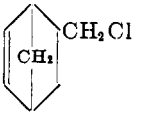
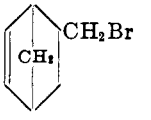
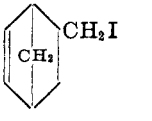
DIENE	DIENOPHILE	TEMPERATURE	PRODUCT	REFERENCE
		°C.		
Cyclopentadiene ...	1-Nitro-1-propene	100–110		(20)
Cyclopentadiene ...	1-Nitro-1-butene	100–110		(20)
Cyclopentadiene† ..	Dihydrothiophene dioxide	180		(20)
Cyclopentadiene ...	Vinyl-*p*-tolyl sulfide	100		(20)
Cyclopentadiene ...	Allyl alcohol	175–180		(40)
Cyclopentadiene ...	Crotyl alcohol	175–180		(40)
Cyclopentadiene ...	Allyl chloride	175–180		(40)
Cyclopentadiene ...	Allyl bromide	175–180		(40)
Cyclopentadiene ...	Allyl iodide	100		(40)

TABLE 1—*Continued*

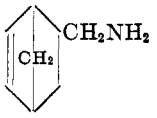
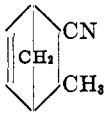
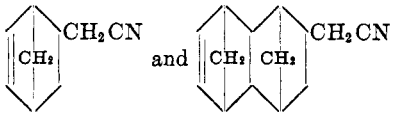
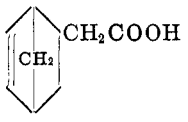
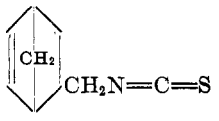
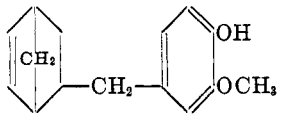
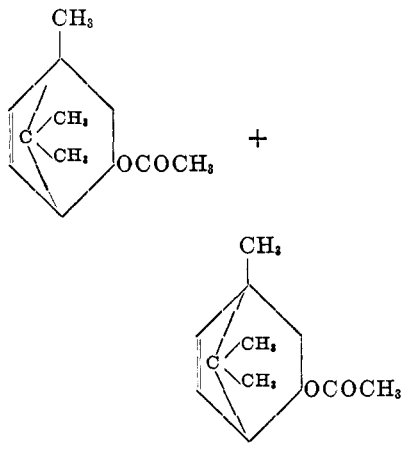
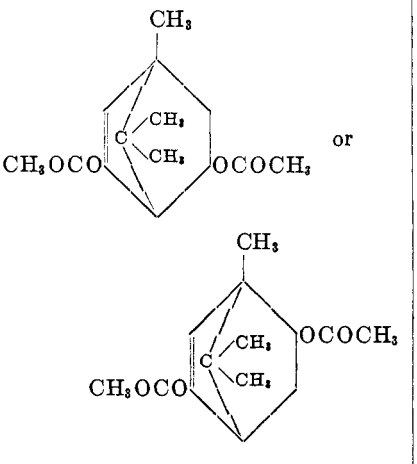
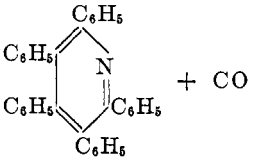
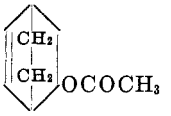
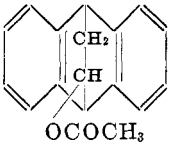
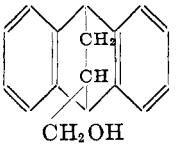
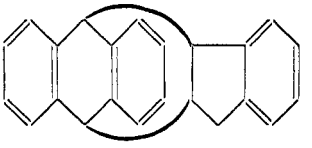
DIENE	DIENOPHILE	TEMPERATURE	PRODUCT	REFERENCE
		°C.		
Cyclopentadiene§ ..	Allylamine	175–180		(40)
Cyclopentadiene ...	Crotononitrile			(246)
Cyclopentadiene† ..	Vinylacetonitrile	175–180		(40)
Cyclopentadiene ...	Vinylacetic acid	175–180		(40)
Cyclopentadiene ...	Allyl isothiocyanate	175–180		(40)
Cyclopentadiene ...	Eugenol	175–180		(40)
1,1,2-Trimethylcyclopentadiene¶.	Vinyl acetate	235–240		(44)

TABLE 1—*Concluded*

DIENE	DIENOPHILE	TEMPERATURE	PRODUCT	REFERENCE
		°C.		
Methyl β-camphylate.....	Vinyl acetate	230		(44)
Tetraphenylcyclopentadienone.....	Benzonitrile	Reflux		(181)
1,3-Cyclohexadiene.	Vinyl acetate	180		(19)
Anthracene.....	Vinyl acetate	180		(19)
Anthracene.....	Allyl alcohol	210–220		(40)
Anthracene.....	Indene	200–210		(291)

* Product is mainly 4-vinylcyclohexene, formed by dimerization of butadiene.

† The second product results from the addition of cyclopentadiene to the first product.

‡ Catalytic reduction of the adduct gave a nitro compound which yielded norbornylamine on reduction with zinc dust and acetic acid.

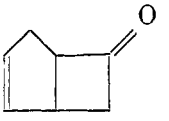
§ This adduct undergoes ring enlargement on treatment with nitrous acid, yielding 1,4-endomethylene-2-cyclohepten-6-ol.

¶ The *dl*-dehydrobornyl acetate was reduced and the product degraded to camphor.

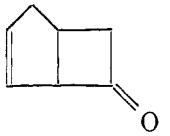
D. Ketenes

Ketene, $H_2C{=}C{=}O$, bears the same relationship to the carbonylenic dienophiles as the allenes bear to the conjugated dienes. Addition of dienes to the ketenes does not occur according to the diene synthesis. In a number of cases, 1,2-addition of dienes to ketenes does occur to form fused-ring derivatives of cyclobutanone. This reaction differs in no essential respect (Staudinger) from the reactions of ketenes with monoölefinic compounds, for these types also form fused-ring derivatives of cyclobutanone if the olefin itself is cyclic. Straight-chain olefins and diolefins form straight-chain cyclobutanone derivatives.

Cyclopentadiene has been reported to react with ketene (96), but this is disputed by Smith and his students (336). Brooks and Wilbert (96) obtained a cyclobutanone derivative, in which the location of the double bond is uncertain. The compound may have either structure I or structure II.

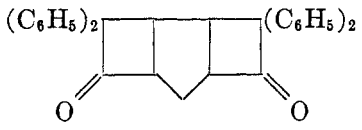


I

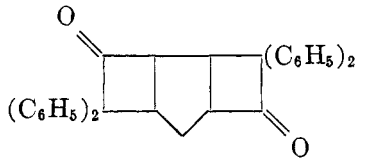


II

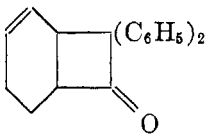
Diphenylketene and cyclopentadiene react at room temperature to yield the diphenyl derivative of I, according to Smith (336); Farmer and Farooq (198) report the product to be the diphenyl derivative of II. Reaction at higher temperatures results in the addition of a second mole of diphenylketene during a period of nine days (336) to give either III or its isomer IV. 1,3-Cyclohexadiene (198) gives V. By way of comparison, cyclopentene (336) gives VI and cyclohexene (198) gives VII.



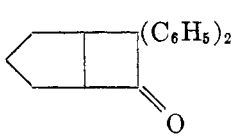
III



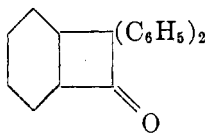
IV



V

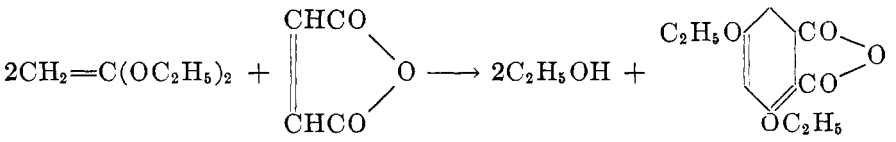


VI



VII

Ketene acetals may react in a unique manner with certain dienophiles. Condensation between 2 moles of ketene diacetal and 1 mole of maleic anhydride gives a diethoxydihydrophthalic anhydride (415):



Dimethylmaleic anhydride does not react, and the reactions with *p*-benzoquinone and with benzalacetophenone proceed normally to give cyclobutane derivatives, but acetylenedicarboxylic ester yields 3,5-diethoxyphthalic ester (415).

E. Quinones as dienophiles

The majority of diene syntheses employing *p*-benzoquinone and α-naphthoquinone will be discussed in connection with the reactions of the various dienes and enynes. There are also a few other quinones mentioned elsewhere in this review, particularly with reference to the reactions of polynuclear hydrocarbons as dienes.

The quinones to be discussed include the true quinones—those which may be derived from aromatic compounds by direct oxidation—and those partially hydrogenated quinones which result from interaction of a diene and a true quinone. Of the various types of quinones and quinonoid substances, those derived from or benzologous with *p*-benzoquinone have been studied most extensively. Some work has been done with quinones derived from or benzologous with *o*-benzoquinones, and certain compounds such as the quinonoid form of 2,4-dinitrobenzeneazo-*p*-phenol have been shown to possess dienophilic properties.

(*1*) *p-Quinones:* There are definite limitations as to the types of quinones which will act as dienophiles by virtue of the quinonoid structure. While *p*-benzoquinone will add 2 moles of a diene, the addition of the second mole occurs with somewhat greater difficulty than the addition of the first. Fusion of a completely aromatic ring to the *p*-benzoquinone nucleus will completely suppress addition of the second mole of diene, although there is little or no effect on the addition rate for the first mole. α-Naphthoquinone and 1,4-anthraquinone therefore add but 1 mole of diene. Direct fusion of two completely aromatic rings to the *p*-benzoquinone nucleus will suppress all dienophilic properties. Thus 9,10-anthraquinone will not add dienes, but one finds that the two carbonyl groups activate the benzene rings sufficiently so that 9,10-anthraquinone will add a mole of dienophile (153). This is practically the sole case in which a lone benzene ring will add dienophiles, and the case is open to dispute (295). If the ring fused to the *p*-benzoquinone ring is also a *p*-benzoquinone ring, dienophilic properties of the fusion atoms are not destroyed, for naphthacenediquinone adds dienes readily.

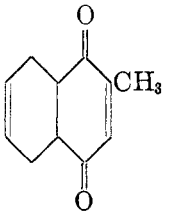
Substituents in the *p*-benzoquinone ring other than fully aromatized rings exhibit a marked hindering effect on the speed of addition of dienes, and often suppress reaction entirely. Addition of dienes to such quinones would result in the formation of adducts possessing angular groups. This is analogous to the effect of substituents attached to the ethylenic carbon atoms of aliphatic dienophiles, which exhibit a less marked hindering effect on the reaction speed, and which also result in the formation of angular or geminal groups and, in one or two cases, spiranes. An exception is observed when the substituent is a group which promotes the entry of an ethylenic compound into the diene reaction, notably the carbonyl group. Groups (such as halogens or hydroxyl) which

can be easily eliminated from the adduct usually have but little hindering effect on the addition.

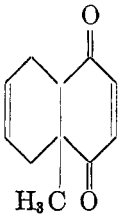
Despite the slowness of the additions observed with quinones possessing substituents attached to the carbon atoms of the carbonylenic double bond, Fieser is most optimistic concerning the possible uses of such quinones for the preparation of compounds related to sterols. This is due, no doubt, to the fact that other methods of synthesizing the sterol ring system are long and tedious and have low over-all yields.

In general, the extent to which quinones possess dienophilic properties (208) parallels their oxidation–reduction potentials. Quinones with high potentials possess greater additive power than those with lower potentials.

Certain of the foregoing statements are well illustrated by the addition of *p*-toluquinone to butadiene (103). One mole of butadiene may add to 1 mole of *p*-toluquinone to give one or both of two possible products, VIII and IX, the latter containing an angular methyl group. The fact that the product does



VIII



IX

not contain such a group is to be anticipated. This addition occurs at temperatures well below 100°C., but the addition of the second mole of butadiene requires temperatures of 150°C. or higher. In spite of the fact that adducts tend to decompose into their generators on heating, the higher temperature is necessary in order to allow the formation of detectable quantities of adduct in reasonable time and also to minimize the polymerization of excess butadiene to 1-vinyl-3-cyclohexene and octahydrobiphenyl.

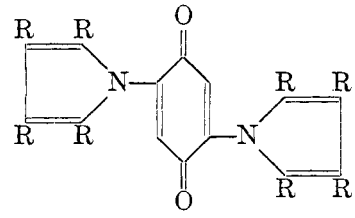
Addition of butadiene to *p*-xyloquinone must necessarily result in the formation of an adduct containing an angular methyl group. The hindering effect of two methyl groups is so great that Chang-Kong and Chin-Tsien (103) observed no addition at 150°C. with benzene as solvent. Adler (7) noted only 10 per cent addition under the same conditions. By using ethanol containing a trace of acetic acid as the reaction medium, Fieser and Seligman (222) were able to add a mole of butadiene to *p*-xyloquinone. 2,3-Dimethylbutadiene was also added to *p*-xyloquinone by the same technique.

A number of patents covering quinone additions (240–245, 247–250) are owned by the I. G. Farbenindustrie Aktiengesellschaft. Most of these were issued at or near the time of the appearance of the first paper by Diels and Alder. These patents cover various phases of the addition of typical dienes to *p*-benzoquinone, α-naphthoquinone, and to their immediate alkyl, hydroxyl, and halogen derivatives. One patent (245) covers the addition of 1 mole of a

diene to *p*-benzoquinone, followed by the addition of a second mole of the same or a different diene to give a hydrogenated 9,10-anthraquinone. The patent is sufficiently broad to cover the additions of tetralinquinone and the other *Bz*-partially hydrogenated α-naphthoquinones.

Quinone additions appear to show steric and electronic hindrance effects to a greater degree than other types of diene syntheses. In addition to steric hindrance effects arising from substituents on the *p*-benzoquinone ring, decrease of dienophilic activity is often noted when substituents are introduced into the benzene rings which may be fused to the quinone ring. Progressive hydroxylation or acetoxylation of the benzene ring of α-naphthoquinone results in diminishing dienophilic activity. Furthermore, substitution in the 1- and 4-positions of the conjugated diene may hinder progress of the diene reaction. If this substituent is joined to both the 1- and the 4-positions so as to form a cyclic diene, activity is usually enhanced. This is probably due to the conjugated system being forced to remain in the (active) *cis*-configuration. Open-chain dienes, such as butadiene, can revert to a *trans*-configuration easily, and the net effect is to halve the concentration of reactive form as compared to cyclopentadiene or cyclohexadiene. Ring formation by bridging a carbonyl group between the 1- and 4-positions of the butadienoid system leads to markedly enhanced ability of the diene to add all types of dienophiles, as strikingly exhibited by the derivatives of cyclopentadienone (*vide infra*). But simple alkyl groups, as in piperylene or 2,4-hexadiene, usually lead to restricted addition of quinones. Arbuzov and Spektermann (62) could obtain addition of only 1 mole of piperylene or of 2,4-hexadiene to *p*-benzoquinone.

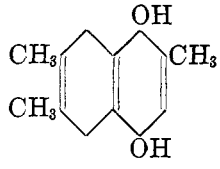
As indicated in the section on nitrogen heterocycles, the reactions of pyrroles with quinones are abnormal. *p*-Benzoquinone adds 2 moles each of 2,5-dimethylpyrrole, 2,3,4-trimethylpyrrole, and 2,4-dimethyl-3-ethylpyrrole (305) to give compounds of the general structure shown in formula X. The by-product in all three cases is quinhydrone, formed by oxidation of the initial product (the *Bz*-tetrahydro derivative of X) by quinone. 2,5-Dibromo-*p*-benzoquinone reacts similarly to give the *BQ*-2,5-dibromo derivatives of the compounds indicated by the general structure X. Apparently the expected loss of hydrogen



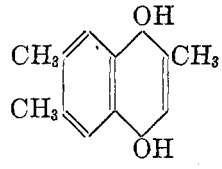
X

bromide from the initial product does not occur, and oxidation occurs preferentially to give the *BQ*-2,5-dibromo derivatives. *p*-Toluquinone appears to react with but 1 mole of 2,5-dimethylpyrrole, giving 2-(2,5-dimethyl-*N*-pyrryl)-5-methyl-*p*-benzoquinone (305). This may be the 4-methyl isomer.

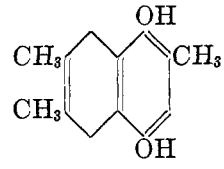
Toluquinone will add piperylene as well as butadiene (103, 222). A trace of hydrogen bromide will rearrange the adduct with 2,3-dimethylbutadiene (85, 103) into a hydroquinone (XI), while heating at 170°C. rearranges the same adduct to a mixture of XII and XIII:



XI



XII

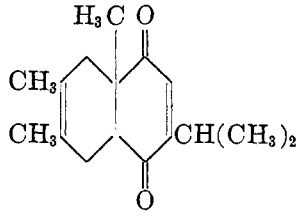


XIII

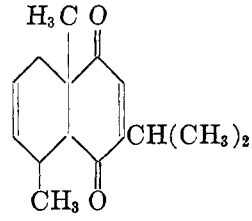
2,3-Diethoxybutadiene adds *p*-toluquinone (255) to give 2-methyl-6,7-diethoxy-5,5a,8,8a-tetrahydronaphthoquinone.

As indicated previously, *p*-xyloquinone will add dienes slowly (7) if at all (103), except under certain solvent conditions (222). The 10 per cent addition obtained by Adler (7) in the addition of butadiene to *p*-xyloquinone was the result of heating four mole proportions of diene with one of the quinone, the diene being in the form of a 20 per cent benzene solution. Heating was conducted at 160–170°C. for 10 hr.

p-Thymoquinone would be expected to behave in much the same manner as *p*-xyloquinone. It adds 2,3-dimethylbutadiene with considerable difficulty to give an oil which presumably has the structure shown in formula XIV. Piperylene is also added (222) to give an adduct assumed to be XV on the assumption that steric factors would prevent proximation of methyl groups. In the assign-



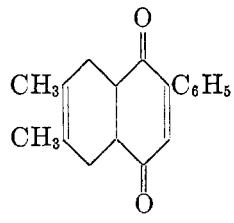
XIV

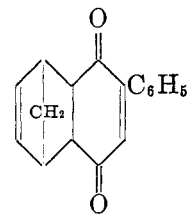


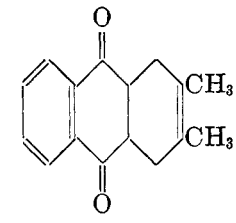
XV

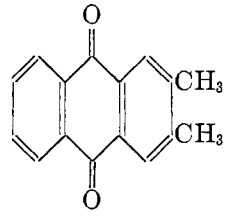
ment of structures XIV and XV it was also assumed that, because the methyl group is of smaller size than the isopropyl group, less difficulty would be encountered in the formation of an angular methyl group than in the formation of an angular isopropyl group.

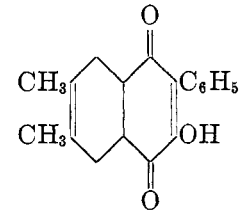
Phenyl-*p*-benzoquinone adds dienes in a manner similar to that of toluquinone, in that the product does not contain an angular group (85). At 100°C. addition occurs with 2,3-dimethylbutadiene and with cyclopentadiene, giving XVI and XVII, respectively. In contrast to the anthraquinone series, in which air oxidation of XVIII yields XIX, atmospheric oxidation of XVI gives XX in a reaction not unlike the formation of hydroxyjuglone from juglone.


XVI


XVII

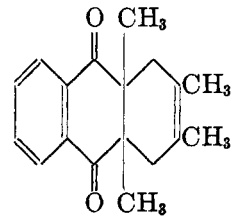

XVIII

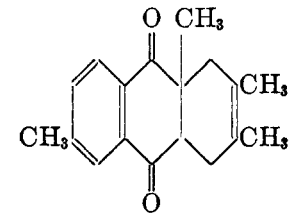

XIX


XX

1,4-Naphthoquinones exhibit the same types of steric hindrance effects as do the *p*-benzoquinones. α-Naphthoquinone itself (290) adds nearly all dienes easily. For example, it adds butadiene to give 1,1a,4,4a-tetrahydro-9,10-anthraquinone (136), 2,3-dimethylbutadiene to give 2,3-dimethyl-1,1a,4,4a-tetrahydro-9,10-anthraquinone (223), cyclopentadiene to give 1,4-endomethylene-1,1a,4,4a-tetrahydro-9,10-anthraquinone (153), and 1,3,5-hexatriene (99) to give what is believed to be 1-vinyl-1,1a,4,4a-tetrahydro-9,10-anthraquinone. Atmospheric oxidation of the hexatriene adduct gives 1-vinyl-9,10-anthraquinone.

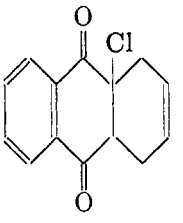
Several alkylated α-naphthoquinones have been studied. All these have at least one methyl group in the 2-position. Because of this, addition to dienes occurs with some difficulty. 2,3-Dimethyl-1,4-naphthoquinone (221) exhibits a very slow reaction with 2,3-dimethylbutadiene, probably forming XXI. This product reverts into its generators when distilled *in vacuo*. 2,6-Dimethyl-1,4-naphthoquinone (221) reacts somewhat more readily than its isomer, giving XXII.


XXI

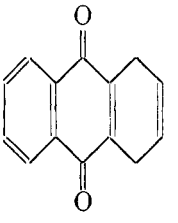

XXII

When α-naphthoquinone is substituted in the 2-position by the hydroxyl group, an adduct is formed which loses water readily to form a 1,4-dihydro-9,10-anthraquinone. Thus 2,3-dimethylbutadiene (208, 222) gives the 2,3-

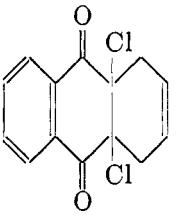
dimethyl derivative. A similar effect is shown by the 2- and 3-halogenated α-naphthoquinones, which lose hydrogen halide to yield more or less fully aromatized 9,10-anthraquinones. Accordingly, butadiene and 2-chloro-1,4-naphthoquinone (208) add to give XXIII, which loses hydrogen chloride easily to give XXIV; and butadiene reacts with 2,3-dichloro-1,4-naphthoquinone to give XXV, which loses 2 moles of hydrogen chloride to give anthraquinone.



XXIII



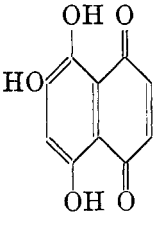
XXIV



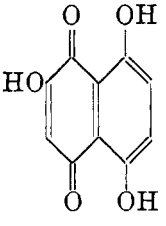
XXV

It was noted previously that progressive hydroxylation or acetoxylation of the benzene nucleus of α-naphthoquinone led to decreased dienophilic activity. Juglone (5-hydroxy-1,4-naphthoquinone) adds 2,3-dimethylbutadiene less readily than does α-naphthoquinone (208). Naphthazarin (5,8-dihydroxy-1,4-naphthoquinone) adds 2,4-hexadiene, piperylene, and alloöcimene (59) with some difficulty; a 6-hr. heating period was necessary to obtain an 83 per cent yield of adduct with 2,3-dimethylbutadiene, whereas only 20 min. heating was necessary in order to obtain a 95 per cent yield of adduct from juglone and 2,3-dimethylbutadiene (208).

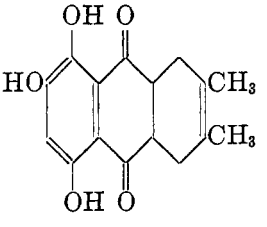
Naphthopurpurin may exist in two tautomeric forms, XXVI and XXVII:



XXVI



XXVII



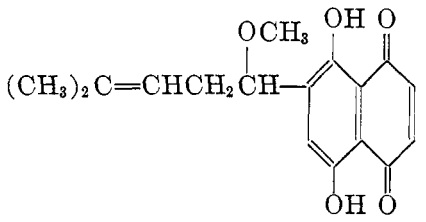
XXVIII

Since XXVII has an inhibiting group attached to the *p*-benzoquinone nucleus, the structure of the naphthopurpurin adduct with 2,3-dimethylbutadiene (208) may be predicted correctly as being XXVIII.

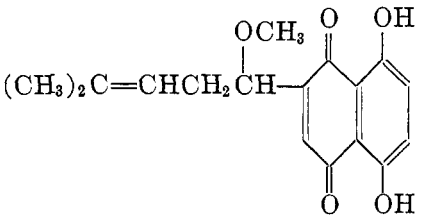
Juglone acetate (208) gives 5-acetoxy-1,1a,4,4a-tetrahydro-2,3-dimethyl-9,10-anthraquinone with 2,3-dimethylbutadiene. Naphthazarin diacetate adds piperylene to yield 1-methyl-5,8-diacetoxy-1,1a,4,4a-tetrahydro-9,10-anthraquinone (175); isoprene gives the 2-methyl isomer. Isomerization of these initial products occurs at the temperature (100°C.) employed to effect these additions, so that the final product obtained is 1-(or 2)-methyl-5,8-diacetoxy-1,2,3,4-tetrahydro-9,10-anthraquinone.

Heating naphthopurpurin triacetate with 2,3-dimethylbutadiene for a period

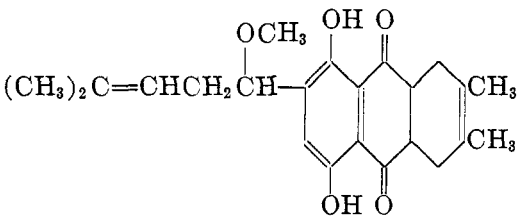
of 27 hr. is necessary in order to obtain the same yield of adduct that may be obtained by heating naphthazarin diacetate with the same diene for a period of only 3 hr. (208). A partially acetylated methylnaphthopurpurin, 2-methyl-8-hydroxy-5,6-diacetoxy-1,4-naphthoquinone (208), will add 2,3-dimethylbutadiene, but only with considerable difficulty. The methyl ether of alkannin (307) is a derivative of naphthazarin and probably exists in two tautomeric forms, XXIX and XXX. It forms an adduct with 2,3-dimethylbutadiene, which is probably XXXI rather than XXXII.



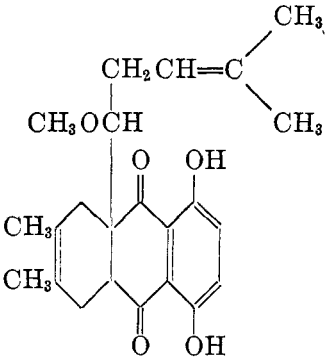
XXIX



XXX



XXXI

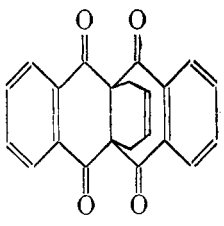


XXXII

The only *p*-quinone derived from aromatic hydrocarbons of three or more fused rings which has been studied with respect to dienophilic properties (aside from 9,10-anthraquinone, which does not add dienes) is 9,10,11,12-naphthacenediquinone. No reports have been found concerning 1,4-anthraquinone, 1,4-naphthacenequinone, 1,4-phenanthrenequinone, or 9,10-naphthacenequinone. It is to be anticipated that all the 1,4-quinones will add dienes, and if the report of the addition of dienophiles to 9,10-anthraquinone can be confirmed, then it is likely that 9,10-naphthacenequinone will also add dienophiles. The addition of 1 mole of anthracene to *p*-benzoquinone gives an adduct which is a derivative of 1,4-anthraquinone; this is 1a,4a,9,10-tetrahydro-9,10-endo-(*o*-phenylene)-1,4-anthraquinone; it is easily oxidized to the 9,10-dihydro derivative. Both of these quinones add dienes.

9,10,11,12-Naphthacenediquinone (202, 203) adds butadiene and 2,3-dimethylbutadiene readily. This addition shows that the fusion of two *p*-benzoquinone rings to each other does not suppress addition of dienes to the

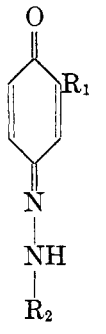
carbon atoms involved in the fusion, for the structure of the butadiene adduct is as shown in formula XXXIII. A similar structure can be assigned to the adduct with 2,3-dimethylbutadiene. This structure follows from the fact



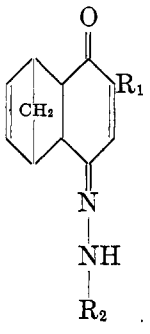
XXXIII

that, by atmospheric oxidation in alkaline solution, phthalic acid and 1,4-dihydro-9,10-anthraquinone are formed.

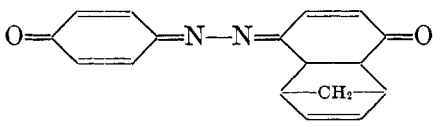
(*2*) *Quinonoid compounds:* Among the nitrogenous analogs of *p*-benzoquinone which add dienes in the diene synthesis (274) are quinone azine and various derivatives of 2,4-dinitrobenzeneazo-*p*-phenol, which exist partly in the tautomeric form (XXXIV). This tautomeric form is the active form in the diene synthesis. In the compounds investigated, R_1 is hydrogen, methyl, or bromine, and R_2 is an aromatic ring which must possess not less than two nitro



XXXIV



XXXV



XXXVI

groups. The adducts of compounds of this type with cyclopentadiene are of the general structure XXXV. The cyclopentadiene adduct of quinone azine has the structure shown in formula XXXVI.

(*3*) *o-Quinones:* The derivatives of *o*-benzoquinone have been investigated recently with regard to their capacities to act as dienophiles. It has been found that those ortho-quinones which possess a comparatively high degree of heat stability will give adducts with dienes. *o*-Benzoquinone and *β*-naphthoquinone are too unstable toward heat to give anything but tarry decomposition products, but a number of substituted *β*-naphthoquinones and certain 1,2- and 3,4-phenanthrenequinones have been shown to possess dienophilic properties. It has been found that 3-substituted 1,2-naphthoquinones add dienes more readily than do 2-substituted 1,4-naphthoquinones. Certain of these additions are complete in 1 hr. at 100°C. (204, 221).

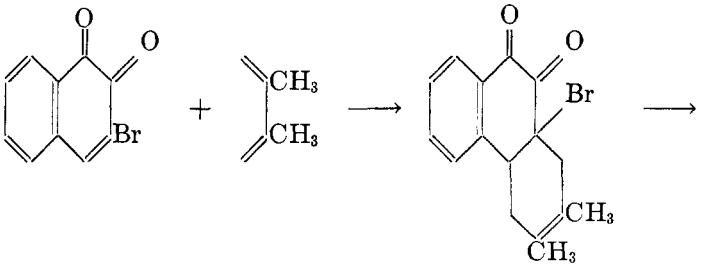
4-Substituted 1,2-naphthoquinones add dienes less readily than do their 3-substituted isomers. The addition of 2,3-dimethylbutadiene and 3-chloro-1,2-naphthoquinone is made complete by heating the components at 100°C. for 1 hr. (204, 221) in chloroform or methylene chloride solution; the product, 1a-chloro-1,1a,4,4a-tetrahydro-2,3-dimethyl-9,10-phenanthrenequinone, will lose hydrogen chloride fairly easily to give 1,4-dihydro-2,3-dimethyl-9,10-phenanthrenequinone. When the adduct is stored in a vacuum desiccator at 10°C., it decomposes to give a green-black amorphous mass. When this material is shaken in air with alcohol or ether, 2,3-dimethyl-9,10-phenanthrenequinone is produced (208).

4-Chloro-1,2-naphthoquinone adds to 2,3-dimethylbutadiene much less readily than does the 3-chloro isomer. The adduct, probably 4a-chloro-1,1a,4,4a-tetrahydro-2,3-dimethyl-9,10-phenanthrenequinone (208), was not isolated; it loses hydrogen chloride more readily than the 1a-chloro isomer, giving the same dihydrodimethylphenanthrenequinone.

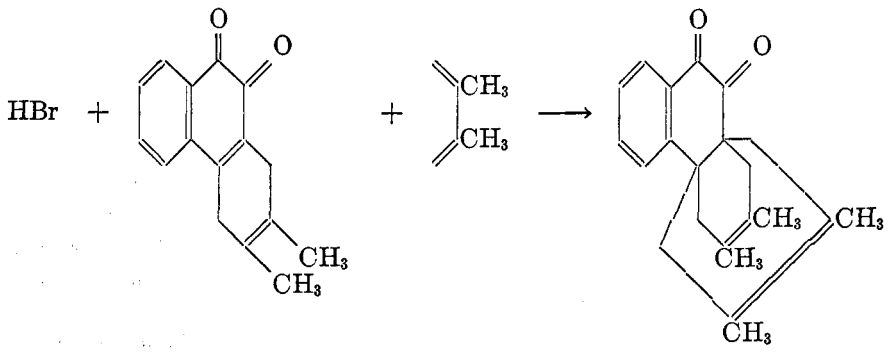
3,4-Dichloro-1,2-naphthoquinone (208) adds 2,3-dimethylbutadiene when heated in chloroform solution for three days at 100°C. The adduct thereby obtained, 1a,4a-dichloro-1,1a,4,4a-tetrahydro-2,3-dimethyl-9,10-phenanthrenequinone, loses hydrogen chloride much less readily than does either of the two preceding adducts. When this does occur, the product is 2,3-dimethyl-9,10-phenanthrenequinone.

Care must be exercised in the preparation of adducts from the chloro-1,2-naphthoquinones, for traces of alcohol are especially deleterious. For this reason medicinal chloroform cannot be used as solvent. Other impurities in the materials used likewise have a deleterious effect on the progress of the reaction, and highly purified materials are required in order to assure good results.

An interesting sequence of reactions may be observed in the addition reaction of 3-chloro-1,2-naphthoquinone (209) and 2,3-dimethylbutadiene. 3-Bromo-1,2-naphthoquinone acts in a similar manner. The halogenated quinone is red; when it is heated with the diene, the color fades to yellow. This is the color of the 1a-halo-1,1a,4,4a-tetrahydro-2,3-dimethyl-9,10-phenanthrenequinone. On further heating, especially in direct sunlight, the red color reappears. Introduction of a second mole of 2,3-dimethylbutadiene, followed by further heating, causes a second fading of the color to yellow. The cause of this sequence of color changes is shown in the skeleton reactions:



(red) (yellow)



(red) (yellow)

The adduct with 2 moles of 2,3-dimethylbutadiene usually loses a mole of the diene in preference to undergoing other reactions. Attempted formation of an oxime results in the loss of a mole of 2,3-dimethylbutadiene and formation of the dioxime of 2,3-dimethyl-1,4-dihydro-9,10-phenanthrenequinone. Pyrolysis in the presence of a mild oxidizing agent results in loss of 2,3-dimethylbutadiene and formation of 2,3-dimethyl-9,10-phenanthrenequinone.

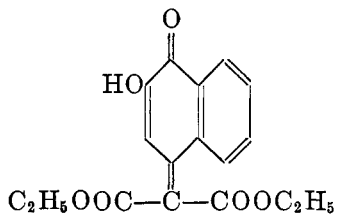
6-Bromo-1,2-naphthoquinone (208) adds 2,3-dimethylbutadiene to give a product which is probably 6-bromo-2,3-dimethyl-1,1a,4,4a-tetrahydro-9,10-phenanthrenequinone.

Although 3,7-dimethyl-1,2-naphthoquinone adds dienes less readily than does 3-chloro-1,2-naphthoquinone, it adds a number of dienes which are not added by 2-methyl-1,4-naphthoquinone (204, 208, 221). A period of three days is required for addition of this quinone to 2,3-dimethylbutadiene by heating in alcoholic solution at 100–105°C., and less drastic conditions result in no addition. The product, 1a,2,3,7-tetramethyl-1,1a,4,4a-tetrahydro-9,10-phenanthrenequinone, is of importance in that it contains an angular methyl group.

In the α-naphthoquinone series it was found that progressive hydroxylation of the benzene ring resulted in decreasing dienophilic activity. The same is true of the β-naphthoquinone series. No reaction was observed (208) between 2,3-dimethylbutadiene and either 6- or 7-hydroxy-1,2-naphthoquinone.

4-Benzyl-1,2-naphthoquinone adds 2,3-dimethylbutadiene in a slow reaction (221) to give an adduct containing an angular benzyl group; the adduct is 1,1a,4,4a-tetrahydro-2,3-dimethyl-4a-benzyl-9,10-phenanthrenequinone.

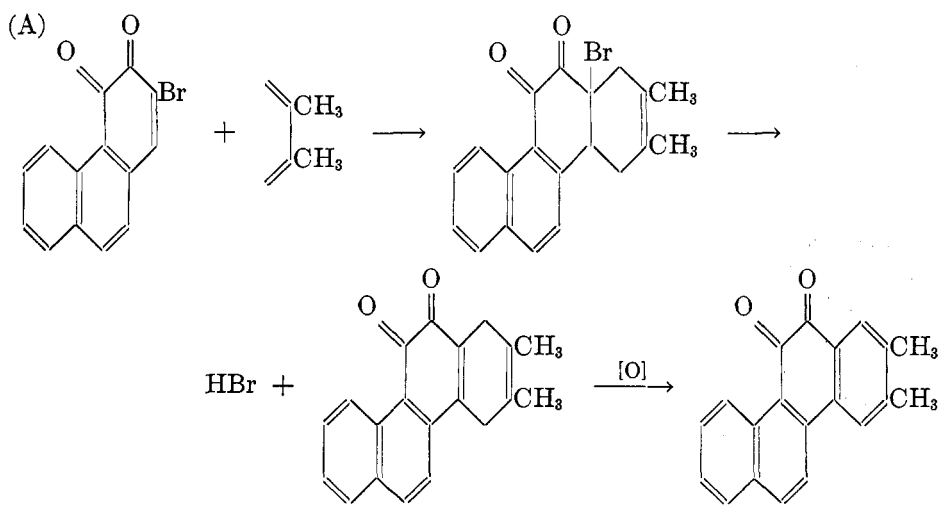
4-(1,2-Naphthoquinonyl)malonic ester may be capable of isomerization into a 1,4-quinone structure (221):



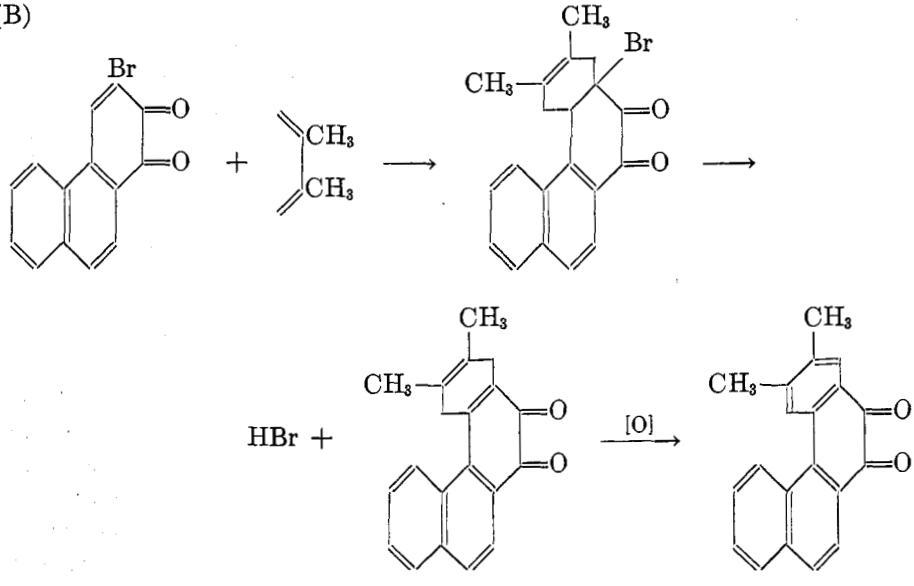
The compound adds 2,3-dimethylbutadiene, but Fieser appears to be reluctant to commit himself as to the structure of the adduct. The adduct may be derived from either the 1,4- or the 1,2-quinonoid structure. One may draw a tentative opinion from the fact that forced addition is usually required to obtain adducts of 4-substituted 1,2-ortho-quinones, and also from the fact that a hydroxyl group attached to the carbonylenic doubly bound carbon atoms does not greatly suppress dienophilic property. This would lead to the opinion that addition would tend to occur with the 1,4-quinonoid form rather than with the 1,2-form. If this be so, then the adduct should lose water on heating, and the product thus formed should be a 1,4-dihydro-2,3-dimethyl-9-methyleneanthrone derivative, decarboxylation and suitable dehydrogenation of which should give the methyleneanthrone itself.

9,10-Phenanthrenequinone does not add dienophiles, and it is also indifferent to dienes. Certain derivatives of 1,2- and 3,4-phenanthrenequinones have been examined by Fieser and Dunn (210); the adducts obtained were identified by degradation to chrysenequinones and benzophenanthrenequinones. The adduct of 2-bromo-3,4-phenanthrenequinone with 2,3-dimethylbutadiene was oxidized to 8,9-dimethyl-5,6-chrysenequinone, hydrogen bromide being eliminated in the first step of the degradation. The yield was 90 per cent on the basis of the generators. 3-Bromo-1,2-phenanthrenequinone gave with dimethylbutadiene an adduct which was oxidized with chromic acid to give 6,7-dimethyl-3,4-benz-9,10-phenanthrenequinone in an over-all yield of 58 per cent, based on the generators. By using butadiene, 3,4-benz-9,10-phenanthrenequinone was prepared from 3-bromo-1,2-phenanthrenequinone. It was found that 1,2-phenanthrenequinone would add 2,3-dimethylbutadiene, but at a slower rate than did the 3-bromo derivative. The latter was easily prepared by direct bromination of 1,2-phenanthrenequinone.

The courses of these syntheses with 2-bromo-3,4-phenanthrenequinone and with 3-bromo-1,2-phenanthrenequinone are given in skeleton equations (A and B) below:



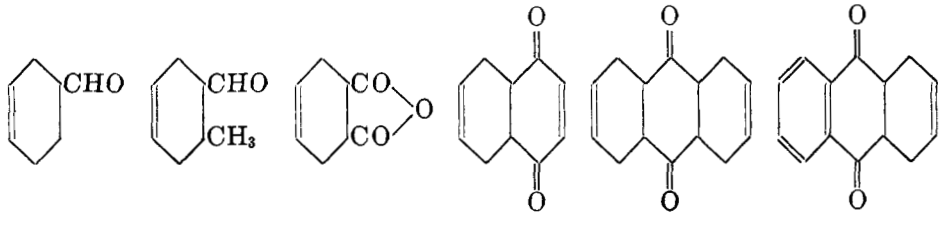
(B)



IV. DIENES: BUTADIENE AND SIMPLE DERIVATIVES

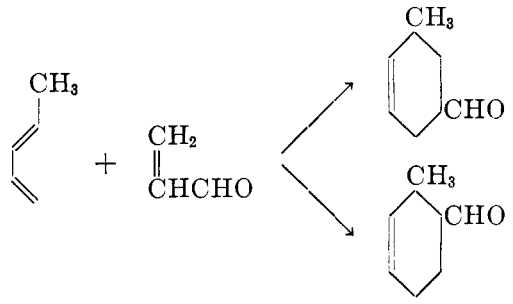
A. Simple derivatives of butadiene

The parent hydrocarbon, butadiene, reacts readily with acrolein (104, 105, 136, 144), crotonaldehyde (144), maleic anhydride (136), *p*-benzoquinone (23, 293), α-naphthoquinone (136), and many other dienophiles to give adducts of formulas which may be anticipated from the general rules for adduct structures which were given on page 320 of this review. The structures of the compounds formed are, respectively:



Piperylene (2,4-pentadiene) reacts with maleic anhydride (144) and with acrolein (63). The product of the latter reaction is illustrative of many cases of adducts the structures of which are problematical. This is always the case when both diene and dienophile do not possess a symmetrical structure with respect to the conjugated system or to the carbonylenic double bond, as the case may be. If either the diene or the dienophile is symmetrical, then the product of a normal diene reaction is of known structure.

The unsymmetrical diene and dienophile, as represented by piperylene and acrolein, may react to give one or both of two possible products:



In this case, the structure of the product can be determined by dehydrogenation to the corresponding xylene. The boiling-point difference between *o*- and *m*-xylenes is not large; hence further confirmation would be desirable, such as oxidation of the xylene to the corresponding phthalic acid. Arbuzov (63) did not employ such a proof, but he gives the structure of the adduct of piperylene and acrolein as that of the meta-aldehyde. The structure of the adduct of maleic anhydride and piperylene may be deduced from the general rules for adduct formation.

There appears to be a substantial difference (309) in the rates of addition of maleic anhydride by the *cis*- and *trans*-isomers of piperylene. The analysis of a pure mixture of *cis*- and *trans*-piperylenes was attempted by Robey and his coworkers, who found that addition ceases between 65 and 78 per cent of completion. This was ascribed to differences in the rates of addition of dienophiles by the two isomers. Arguments for and against their belief that the unreactive form (which was isolated) is the *cis*-isomer may be found in the section dealing with the mechanism and stereochemistry of the diene synthesis (see page 496)[1].

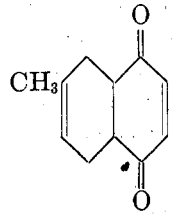
[1] After this review had gone to press, Craig presented a paper before the 104th Meeting of the American Chemical Society at Buffalo, New York. In this paper, Craig showed quite convincingly that *trans*-piperylene (formed by gentle thermal decomposition of piperylene sulfone) adds maleic anhydride readily according to the general rules of diene syntheses. It was also shown that *cis*-piperylene will polymerize before it adds maleic anhydride, thus confirming previous observations. It must be considered, therefore, that the non-addition of maleic anhydride by *cis*-piperylene is a thoroughly established fact. Although cyclopentadiene is certainly of *cis*-configuration, it adds maleic anhydride with great avidity. A possible explanation for the apparent anomaly may be that while the butadienoid configuration of cyclopentadiene is forced to be *cis*, the butadienoid configuration of *cis*-piperylene may be either *cis* or *trans*, or a dynamic equilibrium between the two forms. If the methyl group of *cis*-piperylene exerts a steric hindrance effect upon the free rotation of the vinyl group around the bond linking carbon atoms 3 and 4 (considering *cis*-piperylene to be 2,4-pentadiene), then the butadienoid configuration of *cis*-piperylene may be largely or even exclusively a *trans*-butadienoid configuration at ordinary temperatures. Temperatures required to produce appreciable amounts of the *cis*-butadienoid form or of *trans*-piperylene may be as high as or higher than those required to induce polymerization under the acidic conditions employed (owing to the acid character of maleic anhydride). This question of steric control of the proportions of *cis*- and *trans*-butadienoid forms of a given 1,3-butadiene derivative is deserving of much further study.

Care must be taken in distinguishing between *cis*- and *trans*-isomers of a diene such as piperylene, and *cis*- and *trans*-butadienoid systems. Each isomer of piperylene may exist in both *cis*- and *trans*-butadienoid forms, which probably exist in dynamic equilibrium with each other. Thus *cis*-piperylene exists in *cis*- and *trans*-forms which are in dynamic equilibrium with each other, owing to free rotation about the single bond joining the 2- and 3-carbon atoms of the butadienoid system. In a *cis–trans*-butadienoid system such as this, in which the forms are spontaneously interconvertible, the existence of such a system may be disregarded for all practical purposes.[1]

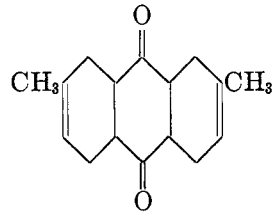
The purest sample of 3,6-dihydrophthalic acid ever made is claimed by Diels and Alder, who prepared it by the addition of acetylenedicarboxylic acid to butadiene in dioxane solution (11). This preparation had a melting point nearly 13°C. higher than the preparation of von Baeyer.

Isoprene reacts with maleic anhydride (144), *p*-benzoquinone (153), and also with itself in dimerization and trimerization reactions (136, 275, 345, and 349) which differ sharply from its polymerization reactions. This dimerization reaction will be considered more fully in a later section (see page 430), but it will be of interest to note here that it and other dimerization reactions (except those of sorbic acid and the cyclopentadienones) are examples of additions which show that the dienophile need not contain double bonds of the carbonylenic type.

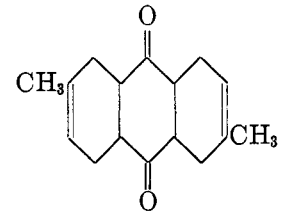
The reaction of isoprene with *p*-benzoquinone is entirely analogous to the reaction of butadiene with this dienophile. The first product of addition (I) may add another mole of isoprene to give either II or III:



I



II



III

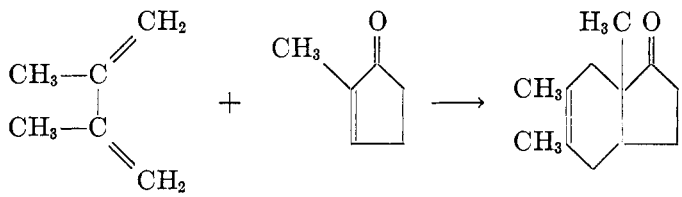
Actually, both products were obtained (153). Structures were proved by atmospheric oxidation to the corresponding dimethylanthraquinones.

2,4-Hexadiene reacts with crotonaldehyde, acrolein, and maleic anhydride (63, 144), but *p*-benzoquinone will add only 1 mole of the diene (62). Owing to the symmetrical nature of the diene, only one structure is possible for each of the adducts obtained thus. However, stereoisomerism is possible in the adducts. This phase of the structure of the adduct appears not to have been investigated.

1,3-Dimethylbutadiene is easily prepared by the method of the Saytzews (325), who obtained a hexadiene through the interaction of acetone, allyl bromide, and an alkali metal. The constitution of the product was not definitely established at the time, but the possibilities were limited to 1,3-dimethylbutadiene and 2-methyl-1,4-pentadiene. The latter substance does not possess

the conjugated system required of dienes which undergo the diene synthesis. Inasmuch as Diels and Alder (144) found that the diene reacted with maleic anhydride to give 3,5-dimethyl-1,2,3,6-tetrahydrophthalic anhydride, the structure of the Saytzew diene was established. The same diene was also obtained by pyrolysis of the phosphate of 2-methyl-2,4-diaminopentane (144) and also by dehydration of 2-methylpentene-2,4-glycol (144), as proved by the mutual identities of the adducts of maleic anhydride and also of crotonaldehyde with the products from each of the three sources.

2,3-Dimethylbutadiene has been well studied, both because of its symmetry and because of its ease of preparation. It reacts with 3-hexen-2,5-dione (227), 2-methylcyclopenten-3-one (93), maleic anhydride (144, 199), and acrolein (139, 144) to give adducts of anticipated structures. Of particular interest in this connection is that an angular methyl group is formed in the case of 2-methylcyclopenten-3-one:



2,3-Dimethylbutadiene 2-Methyl-cyclopenten-3-one

When dienophiles are employed which lead to the formation of angular, geminal, or spirane groups, the diene reaction often proceeds more slowly than if the potentially angular, etc., groups of the dienophile were absent. This subject was covered earlier in this review. Thus, the above reaction of 2-methylcyclopenten-3-one with 2,3-dimethylbutadiene is much slower than the reaction of butadiene with cyclopenten-3-one. Even the addition of diacetylethylene is much more rapid than the addition of 1,2-diacetyl-1-propene (227). Where the mode of addition is optional, as in the addition of butadiene to *p*-toluquinone, the product does not contain an angular methyl group.

Having illustrated the simple diene syntheses by citing a number of typical examples, there should be no need of further elucidation of these simple types. For reference and informative purposes, however, there are listed in table 2 the simple butadiene derivatives which have been studied, together with the dienophile employed, the structure of the adduct, and the references to the literature.

With reference to table 2, it should be stated that in some cases the adduct structures are assumed, either by the author of this review or by the original investigators. Several cases will be noted in which addition fails to occur or else gives polymeric products. It may be that normal reaction will occur in a number of cases, provided the proper experimental conditions are determined and employed.[1]

TABLE 2

Diene syntheses with butadiene and simple derivatives

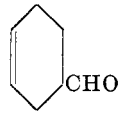
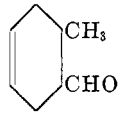
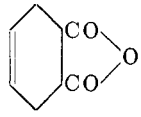
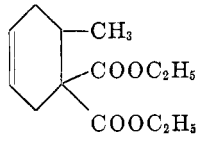
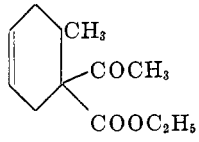
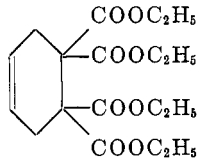
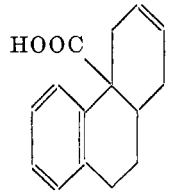
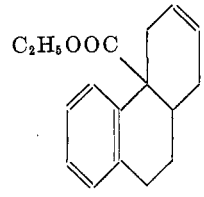
DIENE	DIENOPHILE	PRODUCT	REFERENCE
Butadiene*.....	Acrolein		(104, 105, 136, 144)
Butadiene‡.....	Crotonaldehyde		(105, 144)
Butadiene*.....	Maleic anhydride		(136, 199)
Butadiene‡.....	Ethylidenemalonic ester		(18)
Butadiene‡.....	Ethylideneacetoacetic ester		(18)
Butadiene‡.....	Ethylenetetracarboxylic ester		(18)
Butadiene‡.....	3,4-Dihydro-1-naphthoic acid		(219)
Butadiene‡.....	3,4-Dihydro-1-naphthoic ester		(218)

TABLE 2—*Continued*

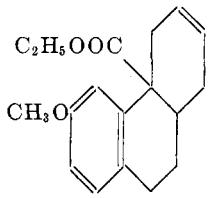
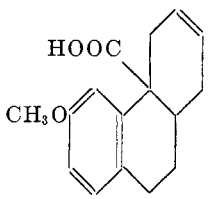
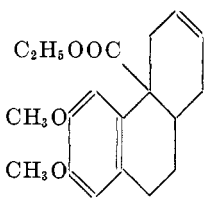
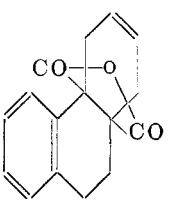
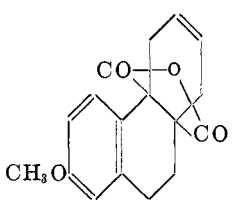
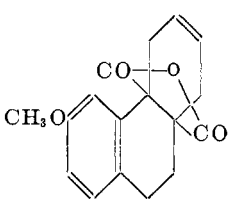
DIENE	DIENOPHILE	PRODUCT	REFERENCE
Butadiene‡.....	7-Methoxy-3,4-dihydro-1-naphthoic ester		(218)
Butadiene‡.....	7-Methoxy-3,4-dihydro-1-naphthoic acid		(219)
Butadiene‡.....	6,7-Dimethoxy-3,4-dihydro-1-naphthoic ester		(218)
Butadiene‡.....	3,4-Dihydro-1,2-naphthalic anhydride		(214, 216)
Butadiene‡.....	6-Methoxy-3,4-dihydro-1,2-naphthalic anhydride		(217)
Butadiene‡.....	7-Methoxy-3,4-dihydro-1,2-naphthalic anhydride		(217)

TABLE 2—*Continued*

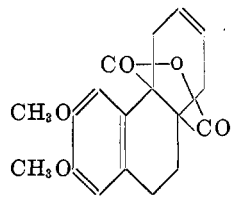
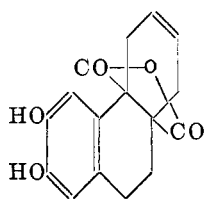
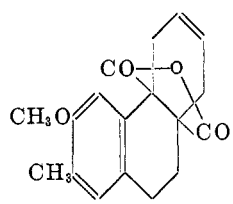
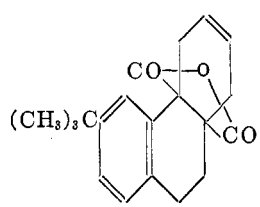
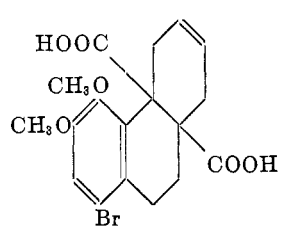
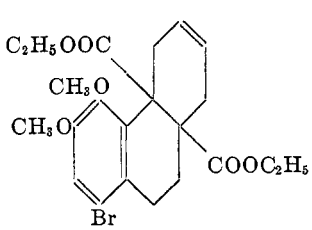
DIENE	DIENOPHILE	PRODUCT	REFERENCE
Butadiene‡.....	6,7-Dimethoxy-3,4-dihydro-1,2-naphthalic anhydride		(217)
Butadiene‡.....	6,7-Dihydroxy-3,4-dihydro-1,2-naphthalic anhydride		(217)
Butadiene‡.....	6-Methyl-7-methoxy-3,4-dihydro-1,2-naphthalic anhydride		(217)
Butadiene‡.....	7-*tert*-Butyl-3,4-dihydro-1,2-naphthalic anhydride		(220)
Butadiene‡.....	7,8-Dimethoxy-5-bromo-3,4-dihydro-1,2-naphthalic acid		(218)
Butadiene‡.....	7,8-Dimethoxy-5-bromo-3,4-dihydro-1,2-naphthalic ester		(218)

TABLE 2—*Continued*

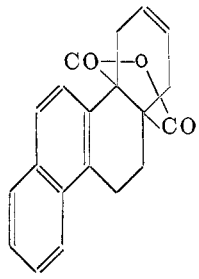
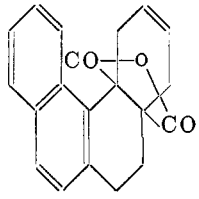
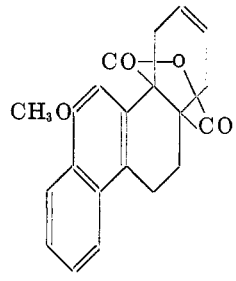
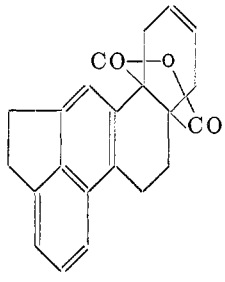
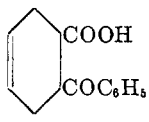
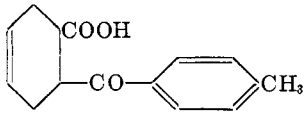
DIENE	DIENOPHILE	PRODUCT	REFERENCE
Butadiene‡.....	3,4-Dihydrophenanthrene-1,2-dicarboxylic anhydride		(212, 213, 216)
Butadiene‡.....	1,2-Dihydrophenanthrene-3,4-dicarboxylic anhydride		(213, 216)
Butadiene‡.....	9-Methoxy-3,4-dihydrophenanthrene-1,2-dicarboxylic anhydride		(217)
Butadiene‡.....	8,9-Ethylene-3,4-dihydrophenanthrene-1,2-dicarboxylic anhydride		(213)
Butadiene‡.....	β-Benzoylacrylic acid		(211, 215)
Butadiene‡.....	β-*p*-Toluoylacrylic acid		(215)

TABLE 2—*Continued*

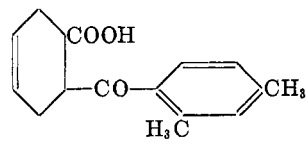
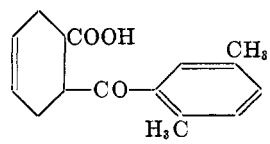
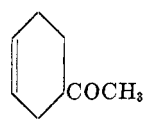
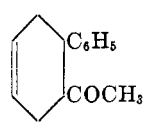
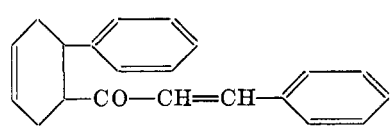
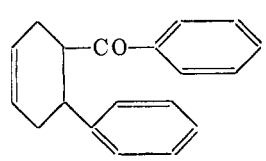
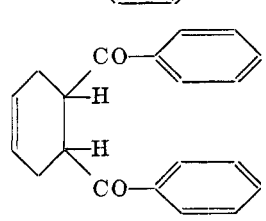
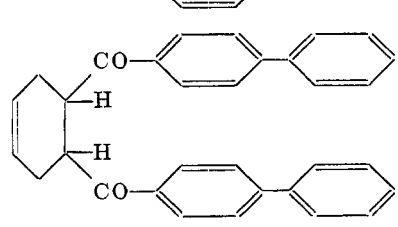
DIENE	DIENOPHILE	PRODUCT	REFERENCE
Butadiene‡.....	β-(2,4-Dimethylbenzoyl)acrylic acid		(215)
Butadiene‡.....	β-(2,5-Dimethylbenzoyl)acrylic acid		(215)
Butadiene‡.....	Acetylethylene		(420)
Butadiene‡.....	Benzalacetone		(297)
Butadiene.....	Ethylene	Cyclohexene	(411)
Butadiene‡.....	Dibenzalacetone		(297)
Butadiene‡.....	Benzalacetophenone		(297)
Butadiene‡.....	*trans*-1,2-Dibenzoylethylene		(3, 6)
Butadiene‡.....	*trans*-1,2-Dixenoylethylene		(4)

TABLE 2—*Continued*

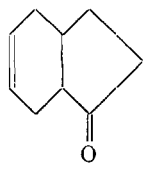
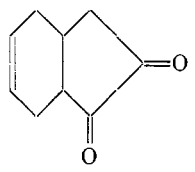
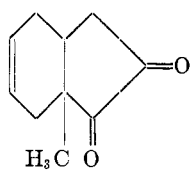
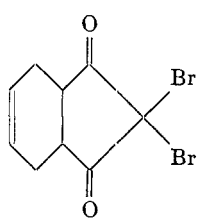
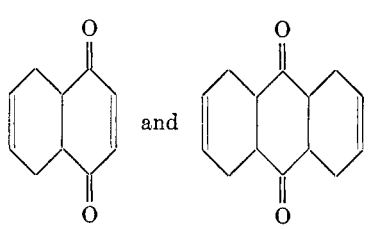
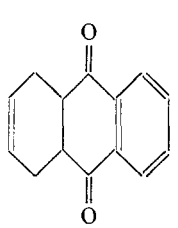
DIENE	DIENOPHILE	PRODUCT	REFERENCE
Butadiene‡.....	1-Cyclopenten-3-one		(129)
Butadiene‡.....	1-Cyclopenten-3,4-dione		(134)
Butadiene‡.....	2-Methyl-1-cyclopenten-3,4-dione		(132)
Butadiene‡.....	4,4-Dibromo-1-cyclopenten-3,5-dione		(129)
Butadiene*.....	*p*-Benzoquinone		(23, 293)
Butadiene*.....	1,4-Naphthoquinone		(136)

TABLE 2—*Continued*

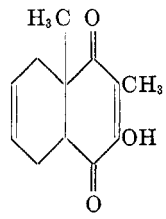
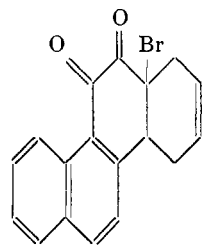
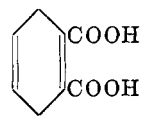
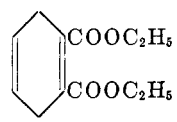
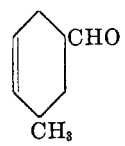
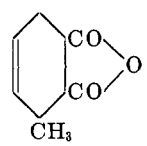
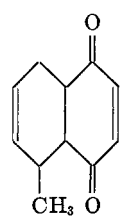
DIENE	DIENOPHILE	PRODUCT	REFERENCE
Butadiene†	2,6-Dimethyl-3-hydroxy-1,4-benzoquinone		(132)
Butadiene‡	2-Bromo-3,4-phenanthrenequinone		(210)
Butadiene‡	Acetylenedicarboxylic acid		(11)
Butadiene‡	Acetylenedicarboxylic ester		(11)
Piperylene*	Acrolein		(63)
Piperylene‡	Maleic anhydride		(144)
Piperylene‡	*p*-Benzoquinone		(62)

TABLE 2—*Continued*

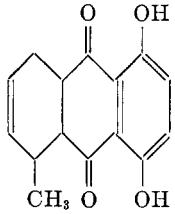
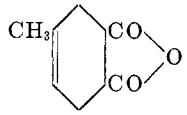
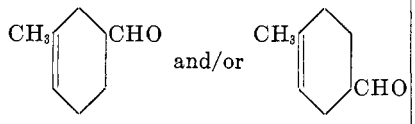
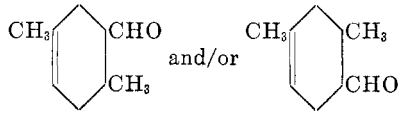
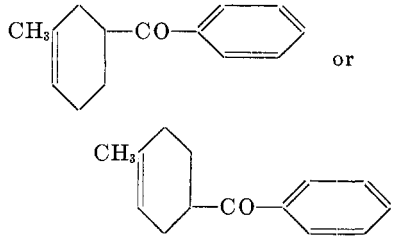
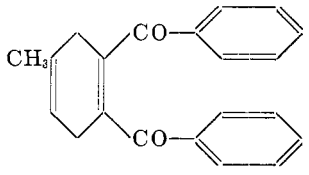
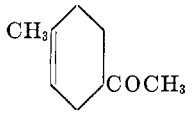
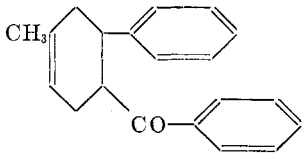
DIENE	DIENOPHILE	PRODUCT	REFERENCE
Piperylene‡.....	Naphthazarin		(59)
Isoprene*.....	Maleic anhydride		(144)
Isoprene.....	Acrolein		(139)
Isoprene.....	Crotonaldehyde		(144)
Isoprene.....	Benzoylethylene		(47)
Isoprene‡.....	Dibenzoylacetylene		(193)
Isoprene†.....	Acetylethylene		(420)
Isoprene†.....	Benzylideneacetophenone		(297)

TABLE 2—*Continued*

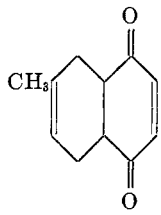
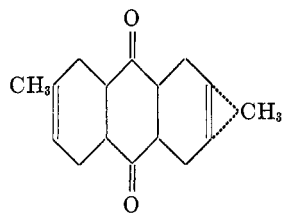
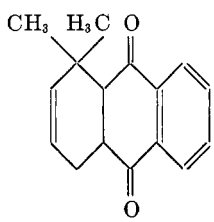
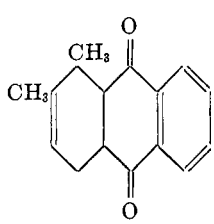
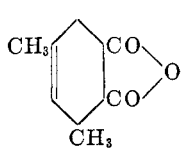
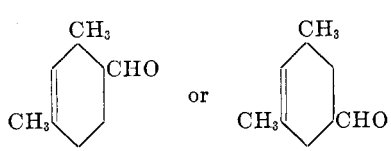
DIENE	DIENOPHILE	PRODUCT	REFERENCE
Isoprene*.....	*p*-Benzoquinone	 and both 	(153, 195)
1,1-Dimethyl butadiene‡.....	Maleic anhydride	"Waxy polymeric anhydride"	(68, 390)
1,1-Dimethylbutadiene‡.....	1,4-Naphthoquinone		(224)
1,2-Dimethylbutadiene‡.....	1,4-Naphthoquinone		(223)
1,3-Dimethylbutadiene‡.....	Maleic anhydride		(68, 105, 278, 390)
1,3-Dimethylbutadiene†.....	Acrolein		(139, 331)

TABLE 2—*Continued*

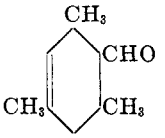
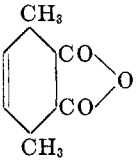
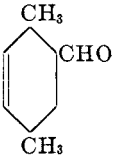
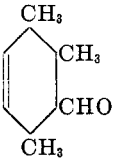
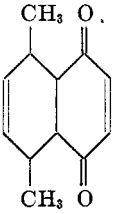
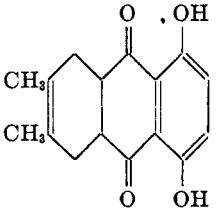
DIENE	DIENOPHILE	PRODUCT	REFERENCE
1,3-Dimethyl-butadiene†	Crotonaldehyde		(105, 139, 144)
1,4-Dimethyl-butadiene‡	Maleic anhydride		(63, 283)
1,4-Dimethyl-butadiene‡	Acrolein		(63)
1,4-Dimethyl-butadiene‡	Crotonaldehyde		(105, 331)
1,4-Dimethyl-butadiene‡	*p*-Benzoquinone		(62)
1,4-Dimethyl-butadiene‡	Naphthazarin		(59)
2,3-Dimethyl-butadiene	Ethylene	1,2-Dimethylcyclohexene	(411)

TABLE 2—*Continued*

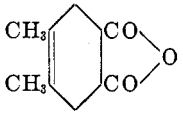
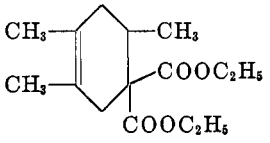
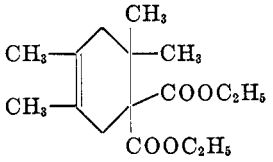
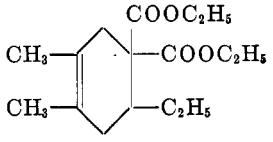
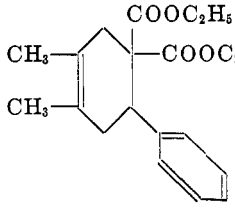
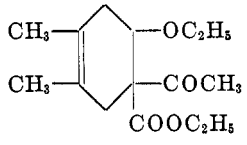
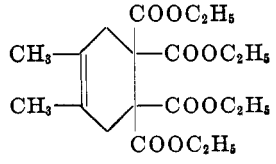
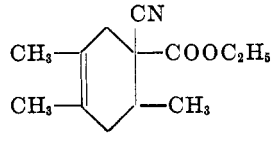
DIENE	DIENOPHILE	PRODUCT	REFERENCE
2,3-Dimethylbutadiene‡.....	Maleic anhydride		(105, 199)
2,3-Dimethylbutadiene‡.....	Ethylidenemalonic ester		(18)
2,3-Dimethylbutadiene‡.....	Isopropylidenemalonic ester		(18)
2,3-Dimethylbutadiene‡.....	*n*-Propylidenemalonic ester		(18)
2,3-Dimethylbutadiene‡.....	Benzylidenemalonic ester		(18)
2,3-Dimethylbutadiene‡.....	Ethoxymethyleneacetoacetic ester		(18)
2,3-Dimethylbutadiene‡.....	Ethylenetetracarboxylic ester		(18)
2,3-Dimethylbutadiene‡.....	Ethylidenecyanoacetic ester		(18)

TABLE 2—*Continued*

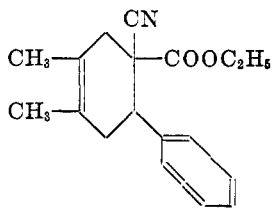
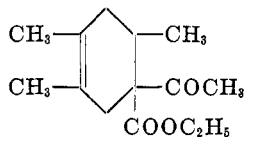
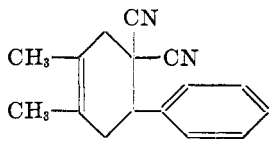
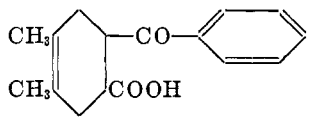
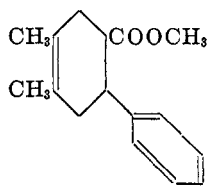
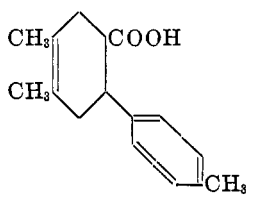
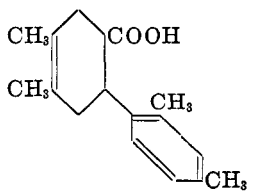
DIENE	DIENOPHILE	PRODUCT	REFERENCE
2,3-Dimethylbutadiene‡.....	Benzylidenecyanoacetic ester		(18)
2,3-Dimethylbutadiene‡.....	Ethylideneacetoacetic ester		(18)
2,3-Dimethylbutadiene‡.....	Benzylidenemalononitrile		(18)
2,3-Dimethylbutadiene‡.....	β-Benzoylacrylic acid		(211, 215)
2,3-Dimethylbutadiene‡.....	Methyl β-benzoylacrylate		(47)
2,3-Dimethylbutadiene‡.....	β-*p*-Toluylacrylic acid		(211, 215)
2,3-Dimethylbutadiene‡.....	β-(2,4-Dimethylbenzoyl)acrylic acid		(211, 215)

TABLE 2—*Continued*

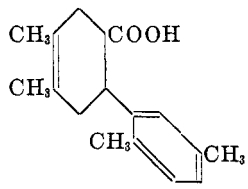
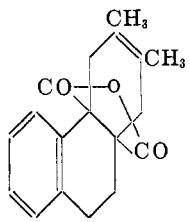
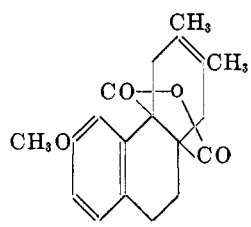
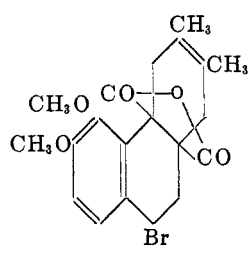
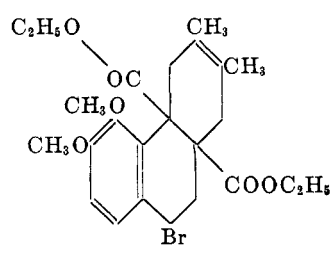
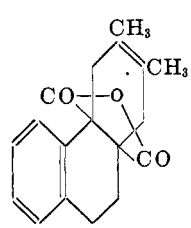
DIENE	DIENOPHILE	PRODUCT	REFERENCE
2,3-Dimethylbutadiene‡	β-(2,5-Dimethylbenzoyl)acrylic acid		(211, 215)
2,3-Dimethylbutadiene‡	3,4-Dihydro-1-naphthoic acid		(219)
2,3-Dimethylbutadiene‡	7-Methoxy-3,4-dihydro-1-naphthoic acid		(219)
2,3-Dimethylbutadiene‡	4-Bromo-7,8-dimethoxy-3,4-dihydro-1-naphthoic acid		(218)
2,3-Dimethylbutadiene‡	4-Bromo-7,8-dimethoxy-3,4-dihydro-1-naphthoic ester		(218)
2,3-Dimethylbutadiene‡	3,4-Dihydro-1,2-naphthalic anhydride		(213, 214, 216)

TABLE 2—*Continued*

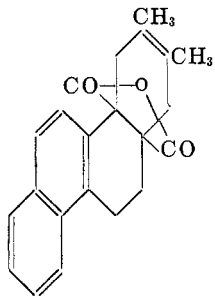
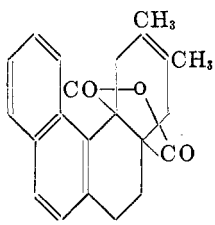
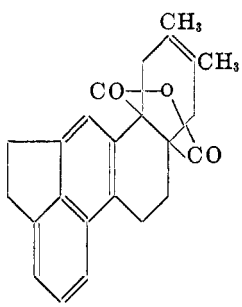
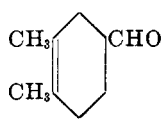
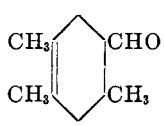
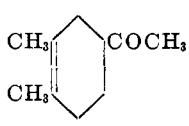
DIENE	DIENOPHILE	PRODUCT	REFERENCE
2,3-Dimethylbutadiene‡.....	3,4-Dihydrophenanthrene-1,2-dicarboxylic anhydride		(213, 216)
2,3-Dimethylbutadiene‡.....	1,2-Dihydrophenanthrene-3,4-dicarboxylic anhydride		(213, 216)
2,3-Dimethylbutadiene‡.....	8,9-Ethylene-3,4-dihydrophenanthrene-1,2-dicarboxylic anhydride		(209, 213)
2,3-Dimethylbutadiene‡.....	Acrolein		(105, 139)
2,3-Dimethylbutadiene‡.....	Crotonaldehyde		(139, 331)
2,3-Dimethylbutadiene‡	Acetylethylene		(420)

TABLE 2—*Continued*

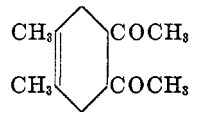
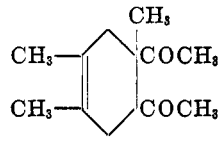
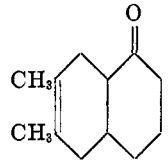
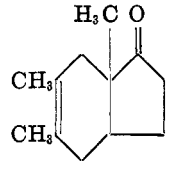
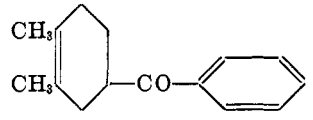
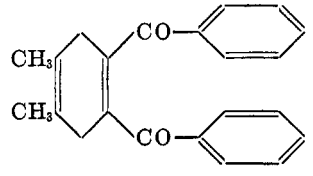
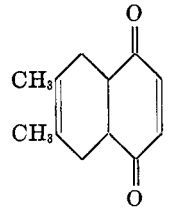
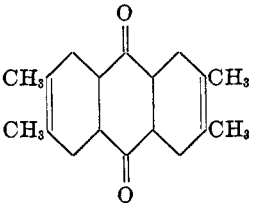
DIENE	DIENOPHILE	PRODUCT	REFERENCE
2,3-Dimethylbutadiene‡.....	1,2-Diacetylethylene		(227)
2,3-Dimethylbutadiene‡.....	1,2-Diacetyl-1-propene		(227)
2,3-Dimethylbutadiene‡.....	Cyclohexen-3-one		(76)
2,3-Dimethylbutadiene‡.....	2-Methylcyclopenten-3-one		(93)
2,3-Dimethylbutadiene‡.....	Benzoylethylene		(47)
2,3-Dimethylbutadiene‡.....	Dibenzoylacetylene		(193)
2,3-Dimethylbutadiene‡.....	*p*-Benzoquinone	 and 	(23)

TABLE 2—*Continued*

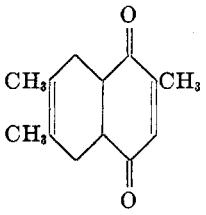
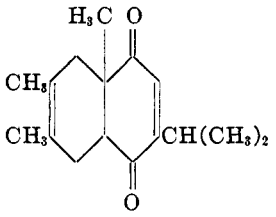
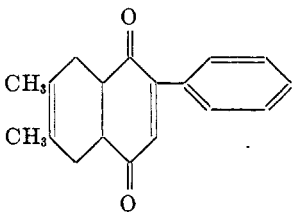
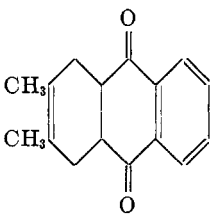
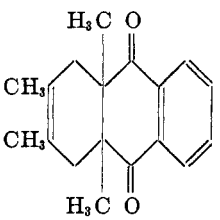
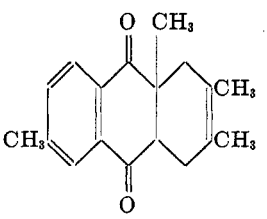
DIENE	DIENOPHILE	PRODUCT	REFERENCE
2,3-Dimethylbutadiene‡.....	*p*-Toluquinone		(85, 103)
2,3-Dimethylbutadiene‡.....	*p*-Thymoquinone		(222)
2,3-Dimethylbutadiene‡.....	Phenyl-*p*-benzoquinone		(85)
2,3-Dimethylbutadiene‡.....	*α*-Naphthoquinone		(223)
2,3-Dimethylbutadiene‡.....	2,3-Dimethyl-1,4-naphthoquinone		(221)
2,3-Dimethylbutadiene‡.....	2,6-Dimethyl-1,4-naphthoquinone		(221)

TABLE 2—*Continued*

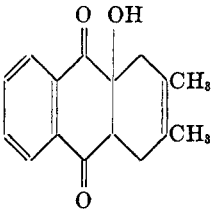
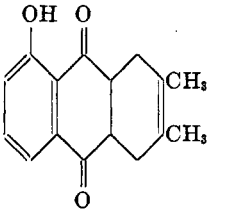
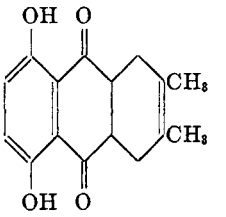
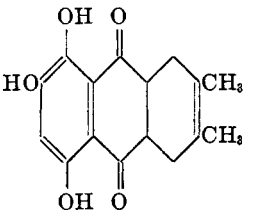
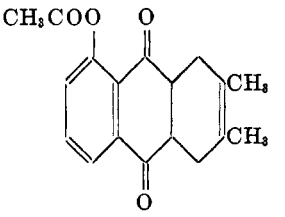
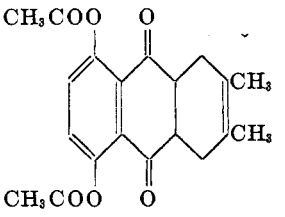
DIENE	DIENOPHILE	PRODUCT	REFERENCE
2,3-Dimethyl-butadiene‡.....	2-Hydroxy-1,4-naphthoquinone		(208, 222)
2,3-Dimethyl-butadiene‡.....	Juglone		(208)
2,3-Dimethyl-butadiene‡.....	Naphthazarin		(208)
2,3-Dimethyl-butadiene‡.....	Naphthopurpurin		(208)
2,3-Dimethyl-butadiene‡.....	Juglone acetate		(208)
2,3-Dimethyl-butadiene‡.....	Naphthazarin diacetate		(208)

TABLE 2—*Continued*

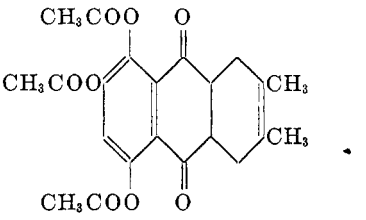
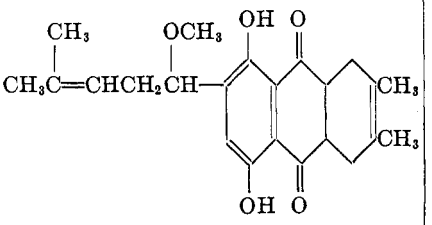
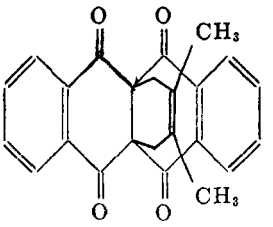
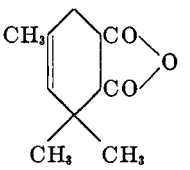
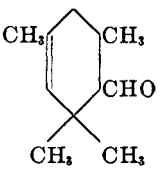
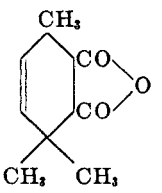
DIENE	DIENOPHILE	PRODUCT	REFERENCE
2,3-Dimethyl-butadiene‡.....	Naphthopurpurin triacetate		(208)
2,3-Dimethyl-butadiene‡.....	Alkannin methyl ether		(307)
2,3-Dimethyl-butadiene‡.....	Naphthacenedi-quinone		(202, 203)
1,1,3-Trimethyl-butadiene†.....	Maleic anhydride		(144)
1,1,3-Trimethyl-butadiene†.....	Crotonaldehyde		(144)
1,1,4-Trimethyl-butadiene‡.....	Maleic anhydride		(68)

TABLE 2—*Continued*

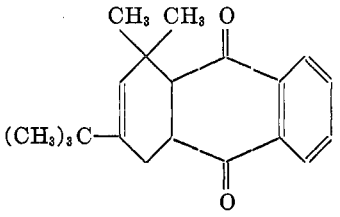
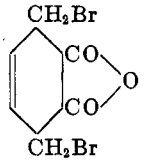
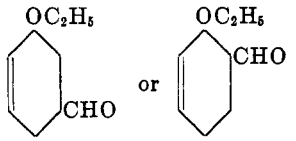
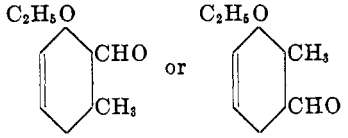
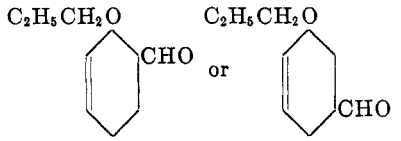
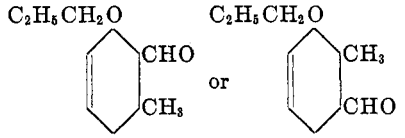
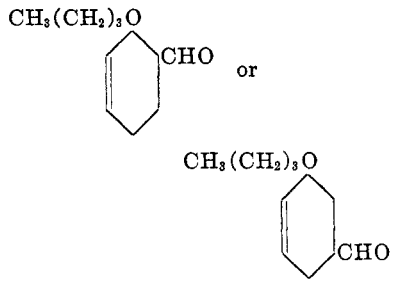
DIENE	DIENOPHILE	PRODUCT	REFERENCE
1-Isopropylbutadiene.....	Maleic anhydride	"Waxy polymeric adduct"	(68)
3-*tert*-Butyl-1,1-dimethylbutadiene‡.....	α-Naphthoquinone		(224)
1,4-Di(bromomethyl)butadiene‡.....	Maleic anhydride		(137)
1-Ethoxybutadiene†.....	Acrolein		(358)
1-Ethoxybutadiene†.....	Crotonaldehyde		(358)
1-*n*-Propoxybutadiene†.....	Acrolein		(358)
1-*n*-Propoxybutadiene†.....	Crotonaldehyde		(358)
1-*n*-Butoxybutadiene†.....	Acrolein		(358)

TABLE 2—*Continued*

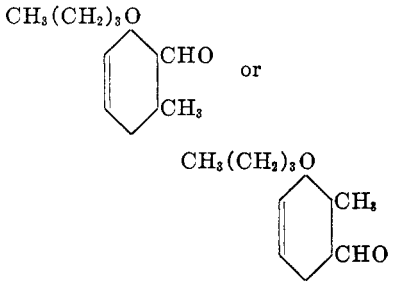
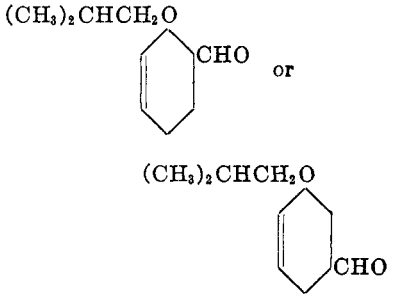
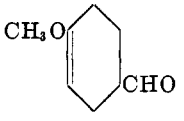
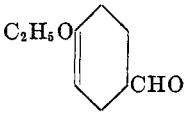
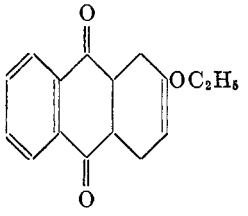
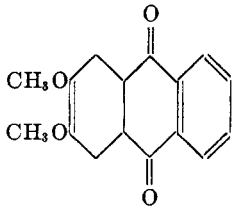
DIENE	DIENOPHILE	PRODUCT	REFERENCE
1-*n*-Butoxybutadiene†	Crotonaldehyde		(358)
1-Isobutoxybutadiene†	Acrolein		(358)
2-Methoxybutadiene†	Acrolein		(419)
2-Ethoxybutadiene†	Acrolein		(419)
2-Ethoxybutadiene†	α-Naphthoquinone		(402)
2,3-Dimethoxybutadiene‡	α-Naphthoquinone		(255)

TABLE 2—*Continued*

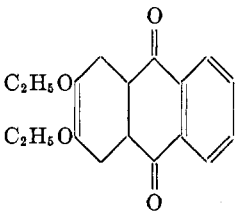
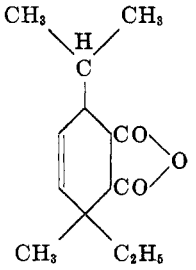
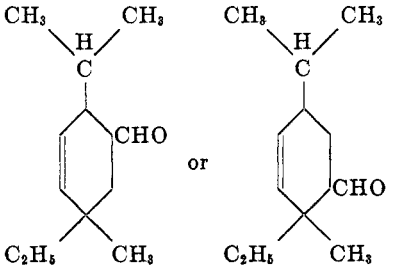
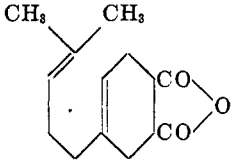
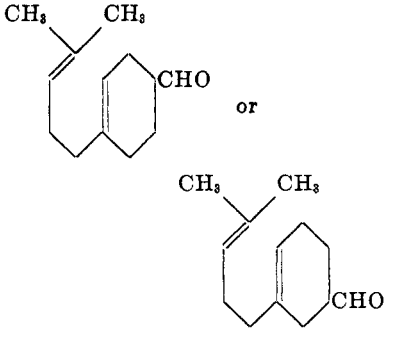
DIENE	DIENOPHILE	PRODUCT	REFERENCE
2,3-Diethoxybutadiene‡.....	α-Naphthoquinone		(255)
2,6-Dimethyl-3,5-octadiene‡.....	Maleic anhydride		(192)
2,6-Dimethyl-3,5-octadiene†.....	Acrolein		(192)
Myrcene‡.....	Maleic anhydride		(43, 144, 407)
Myrcene†.....	Acrolein		(139)

TABLE 2—*Continued*

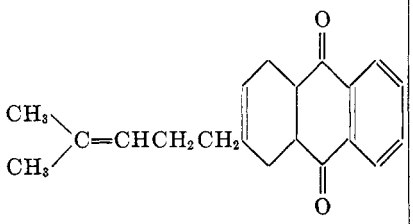
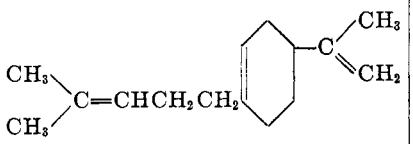
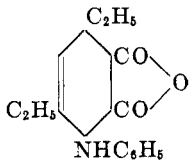
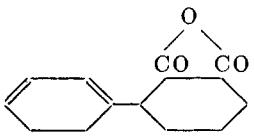
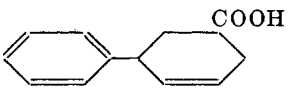
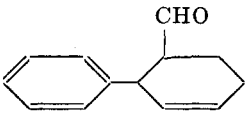
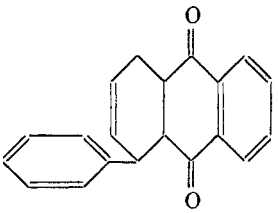
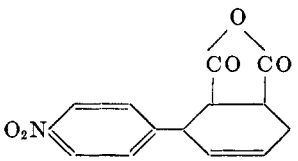
DIENE	DIENOPHILE	PRODUCT	REFERENCE
Myrcene†	α-Naphthoquinone		(224)
Myrcene†	Isoprene	 or isomers	(315)
1,3-Diethyl-4-(*N*-anilino) butadiene	Maleic anhydride		(423, 424)
1-Phenylbutadiene‡	Maleic anhydride		(17, 152)
1-Phenylbutadiene*	Acrylic acid		(277, 281)
1-Phenylbutadiene*	Acrolein		(277, 281)
1-Phenylbutadiene‡	α-Naphthoquinone		(153)
1-*p*-Nitrophenylbutadiene‡	Maleic anhydride		(88)

TABLE 2—*Continued*

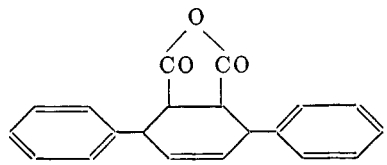
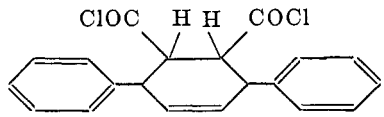
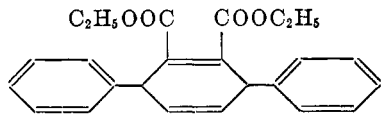
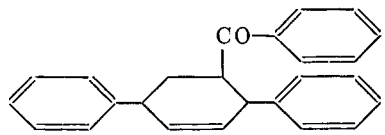
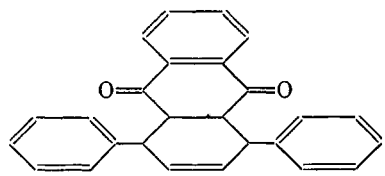
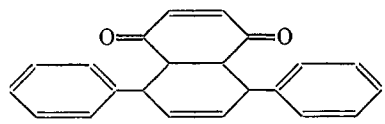
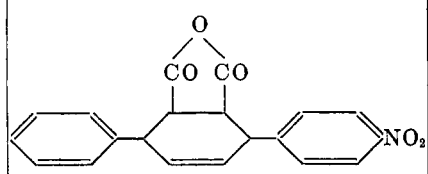
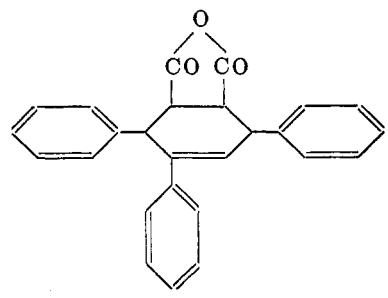
DIENE	DIENOPHILE	PRODUCT	REFERENCE
1,4-Diphenyl-butadiene‡.....	Maleic anhydride		(273)
1,4-Diphenyl-butadiene‡.....	Fumaroyl chloride		(273)
1,4-Diphenyl-butadiene‡.....	Acetylenedicarboxylic ester		(288)
1,4-Diphenyl-butadiene‡.....	Benzoylethylene		(47)
1,4-Diphenylbutadiene‡.....	α-Naphthoquinone		(425)
1,4-Diphenylbutadiene‡.....	*p*-Benzoquinone		(425)
1-Phenyl-4-(*p*-nitrophenyl) butadiene‡.....	Maleic anhydride		(88)
cis-1,2,4-Triphenylbutadiene‡.....	Maleic anhydride		(87)

TABLE 2—*Continued*

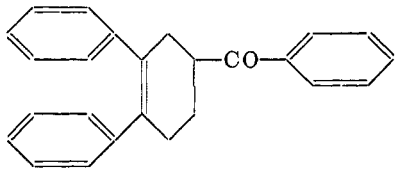
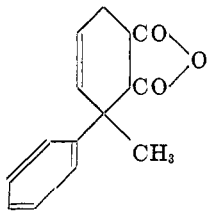
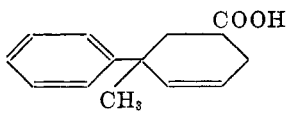
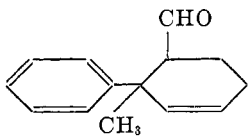
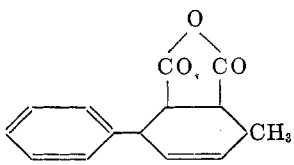
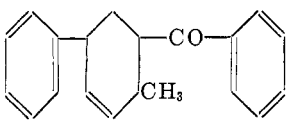
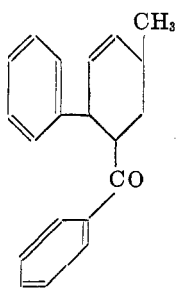
DIENE	DIENOPHILE	PRODUCT	REFERENCE
trans-1,2,4-Triphenylbutadiene	Maleic anhydride	No reaction	(87)
2,3-Diphenylbutadiene‡.....	Benzoylethylene		(47)
1-Phenyl-1-methylbutadiene‡.....	Maleic anhydride		(279)
1-Phenyl-1-methylbutadiene†...	Acrylic acid		(279)
1-Phenyl-1-methylbutadiene*...	Acrolein		(277, 279)
1-Phenyl-4-methylbutadiene‡...	Maleic anhydride		(144)
1-Phenyl-4-methylbutadiene†...	Benzoylethylene	 or 	(47)

TABLE 2—*Continued*

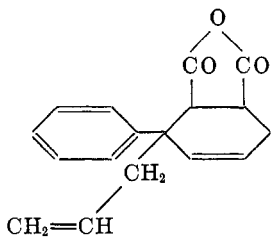
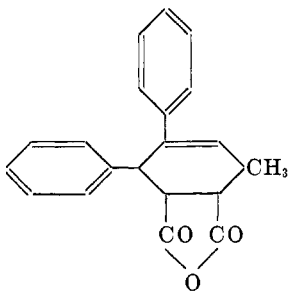
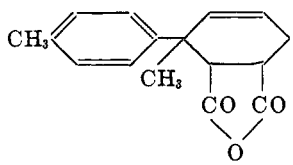
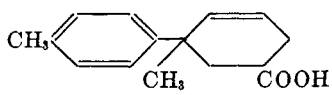
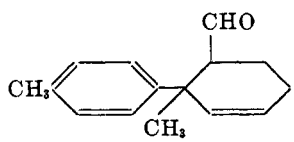
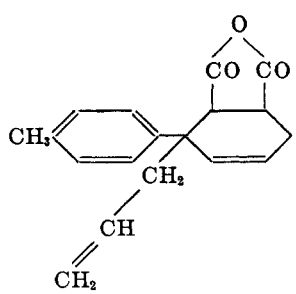
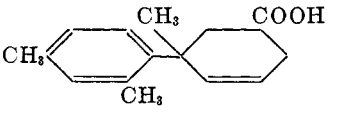
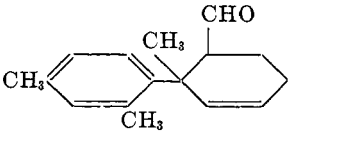
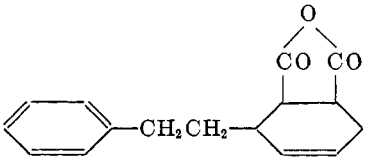
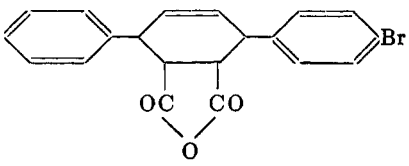
DIENE	DIENOPHILE	PRODUCT	REFERENCE
1-Phenyl-1-allyl-butadiene‡.....	Maleic anhydride		(280)
1,2-Diphenyl-4-methylbu-tadiene‡.....	Maleic anhydride		(87)
1-*p*-Tolyl-1-methylbu-tadiene‡.....	Maleic anhydride		(279)
1-*p*-Tolyl-1-methylbu-tadiene†.....	Acrylic acid		(279)
1-*p*-Tolyl-1-methylbu-tadiene†.....	Acrolein		(277, 279)
1-*p*-Tolyl-1-allyl-butadiene‡.....	Maleic anhydride		(280)

TABLE 2—*Concluded*

DIENE	DIENOPHILE	PRODUCT	REFERENCE
1-(4-*m*-Xylyl)-1-methylbutadiene†	Acrylic acid		(279)
1-(4-*m*-Xylyl)-1-methylbutadiene†	Acrolein		(277, 278, 281)
1-(2-Phenylethyl)-butadiene‡	Maleic anhydride		(122)
1-(2-Phenylethyl)-1-methylbutadiene	Maleic anhydride	Amorphous powder at 110 C.	(122)
1-(2-(*m*-Methoxyphenyl)ethyl)-butadiene	Maleic anhydride	No reaction	(122)
1,2,3,4-Tetraphenylbutadiene	Maleic anhydride	No reaction	(425)
1,4-Di(*p*-anisyl)-butadiene	Maleic anhydride	No reaction	(425)
1-Phenyl-4-*p*-bromophenylbutadiene	Maleic anhydride		(410)
1-(2-(*m*-Methoxyphenyl)ethyl)-butadiene	Acrolein	No reaction	(122)
1,4-Bis(*o*-biphenylene)butadiene	Maleic anhydride	No reaction	(346)

* Structure of adduct proved in literature cited.

† Structure of adduct assumed.

‡ Structure of adduct considered evident because only one structure is possible by the general rules (page 320) of adduct formation.

Referring again to table 2, the adduct of 1-phenyl-1-methylbutadiene and acrylic acid was found in two forms. Theoretically, one might obtain two acids, for it is theoretically possible for the carboxyl group to become located either ortho or meta to the geminal grouping. Each of these two acids should exist in two forms, depending on whether the carboxyl group is *cis* or *trans* with respect to the methyl (or the phenyl) group of the geminal system. Hence four acids are theoretically possible through the addition of acrylic acid to 1-phenyl-1-methylbutadiene. Furthermore, each of the four acids should be resolvable into *d*- and *l*-forms. The above assumes that the *cis*-form of cyclohexene is the only form capable of existence. Now the structure of the adduct resulting from the interaction of 1-phenyl-1-methylbutadiene and acrolein was proved. If the acrylic acid adducts have the formula given in table 2, then oxidation of the acrolein adducts should give one or both of the acids obtained by acrylic acid addition. Oxidation was accomplished by a Cannizzaro reaction (279), and two acids were produced. One of these was identical with an acid obtained by acrylic acid addition, but the other was not. Presuming that the acrolein is added to give a mixture of the *cis*- and the *trans*-forms of the compound given in table 2, then a logical conclusion is that acrylic acid adds to 1-phenyl-1-methylbutadiene to give a mixture of one of the ortho acids with one of the meta acids. While this explains the findings of Lehmann (279), it has not been proved conclusively. The case of 1-phenylbutadiene is related to this specific problem. Its acrolein adduct has the aldehyde group ortho to the geminal system, while its acrylic acid adduct has the carboxyl group meta to that system.

Parallel situations are found in the cases of the acrolein and acrylic acid adducts of 1-*p*-tolyl-1-methylbutadiene and of 1-(2,4-dimethylphenyl)-1-methylbutadiene, and may be amenable to the same explanation. Each forms one acrolein and two acrylic acid adducts. Two acids are formed upon oxidation of the acrolein adduct, only one of which is identical with one of the acrylic acid adducts. Structures of the acrolein adducts were not proved, however.

The structure of the product obtained from *p*-benzoquinone and 1-phenyl 1-methylbutadiene is assumed to be the oxidized adduct shown, because of the extensive reduction of excess quinone to hydroquinone and quinhydrone. The adducts of butadiene with *p*-benzoquinone are easily oxidized to naphtho- and anthra-quinones, the structures of which are those of 5,8-dihydro-1,4-naphthoquinone and 1,4,5,8-tetrahydro-9,10-anthraquinone; this may be accomplished in an alkaline medium at room temperature with atmospheric oxygen. It is logical, therefore, to assume that in the case of 1-phenyl-1-methylbutadiene and *p*-benzoquinone, the hydrogenated quinone ring of the original adduct is completely aromatized by the excess *p*-benzoquinone.

Addition of maleic anhydride to 1,4-diphenylbutadiene appeared to give four isomeric acids melting in the range 198° to 203°C. The form melting at 198°C. decomposed into its generators on distillation. From a stereochemical point of view, two anhydride adducts could be produced in which the phenyl groups are para and *cis* to each other, and one anhydride adduct could be produced

in which the phenyl groups are *trans* to each other. The two *cis*-forms and the one *trans*-form explain three of the four acids observed. The fourth acid may be formed by a change of one of the acids (all of which possess carboxyl groups *cis* to each other) into an acid in which the carboxyl groups are *trans* to each other. For reasons to be discussed later, it is not likely that the anhydride possessing *trans*-phenyl groups is formed in the diene synthesis; therefore it seems more likely that certain of the four acids are the result of isomerizations of the *cis*-phenyl-*cis*-acids which are presumed to be formed initially.

TABLE 3

Reaction of chlorinated dienes with dienophiles

DIENE	REACTION*	REFERENCE
1-Chloro-1,2-butadiene	Negative	(101)
Chloroprene (2-chlorobutadiene)	Positive	(102)
3-Methylchloroprene	Positive	(121)
1-Alkylchloroprenes	Positive	(121, 254)
3,4-Dimethylchloroprene	Positive	(121)
2,3-Dichlorobutadiene	Positive	(89, 121)
1,2,3,5-Tetrachloro-2,4-pentadiene	Negative	(121)
1,3,4-Trichloro-2,4,5-hexatriene	Negative	(121)
3,4-Dichloro-1,2,4,5-hexatetraene	Negative	(121)
1-Chlorobutadiene (α-chloroprene)	Negative	(121)
4-Chloro-1,2,3,4-hexatetraene	Negative	(121)
1,4-Dichloro-2,3,5-hexatriene	Negative	(121)
1,2-Dichlorohexa-3-yne-5-ene	Negative	(121)
3,4-Dichloro-1,3,5-hexatriene	Negative	(121)
1,6-Dichloro-2,3,4-hexatriene	Negative	(121)
4-Chloro-1,2,3,5-hexatetraene	Negative	(121)
1-Chloromethylchloroprene	Positive	(202)
1-Bromomethylchloroprene	Positive	(201)
1-Chloro-5-methoxy-2,3-pentadiene	Negative	(403, 404)
1-Methoxy-3-chloro-2,4-pentadiene	Positive	(403, 404)

* In the eight cases in which addition occurred, the formulas of the products were in accord with those postulated by application of the general rules of adduct formation.

B. Halogenated dienes

Some work has been done on halogenated dienes, particularly by Carothers and his coworkers. With respect to the ability of these dienes to add maleic anhydride or α-naphthoquinone, the following generalizations may be drawn: (*a*) Dienes of the structure Cl—C=C—C=C or C=C(Cl)—C(Cl)=C do not add dienophiles. (*b*) Dienes of the structure C=C(Cl)—C=C, in the absence of other chlorine atoms in the molecule, usually add dienophiles as well as do the parent hydrocarbons.

Table 3 lists chlorodienes which were tested with respect to their ability to add 1,4-naphthoquinone or maleic anhydride. In those cases where reaction occurs, the structure of the product is that predicted by the general rules of

adduct formation. It will be noted that one of these compounds is an allene, while certain others combine the structures of allenes and conjugated dienes.

The conclusion of Carothers was that when the diene reaction is used as a test for conjugation, it is conclusive only when positive. Even so, this may not be strictly true unless reaction is observed at or near room temperature, particularly in the cases of terpenes and sterols. Further, the diene synthesis will not detect *trans*-butadienoid configurations as such. In the cases of terpenes, certain additions occurred when the "diene" contained an isolated-double-bond system or a lone double bond; in one case, the "diene" was a fully saturated compound. All additions in these cases were conducted at elevated temperatures and the same adduct could, in certain instances, be obtained from several different "dienes," which is conclusive proof of isomerization in one or more stages of the addition. These materials did not react readily at room temperature, although the end products postulated for the isomerization of the materials prior to undergoing the diene synthesis reacted readily at room temperature.

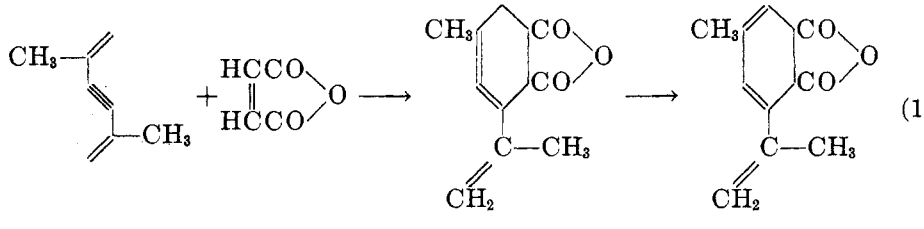
C. Allenes

Dienes containing the grouping C=C=C do not react with dienophiles, provided (*a*) isomerization to a conjugated system does not occur under the conditions of the experiment, and (*b*) the compound under investigation does not contain a conjugated system in addition to the allene system, as in the skeletons C=C=C—C=C and C=C=C—C—C=C—C=C. Certain of these compounds were investigated by Carothers and reported in table 3. The only other studies made were those of 1-cyclohexyl-2,3-pentadiene, which does not add maleic anhydride (2), and of 1-phenyl-1,2-butadiene, which adds neither maleic anhydride nor 1,4-naphthoquinone (1).

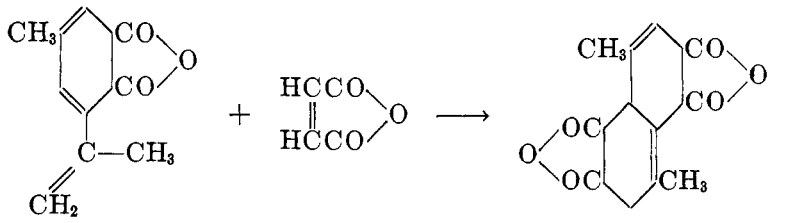
D. Enynes

As indicated in the earlier portions of this review, only a few enynes have been studied. Most of those studied belong to the dienyne class. The field is being opened up, however, by Lewis and Eleanore Butz and their coworkers. At this writing their latest paper is to be read at the 102nd Meeting of the American Chemical Society, and it will deal with enynes in the diene synthesis.

The addition of 2,5-dimethylhexa-1,5-dien-3-yne (100) and maleic anhydride proceeds, probably in two steps, to give a reduced naphthalenetetracarboxylic dianhydride:

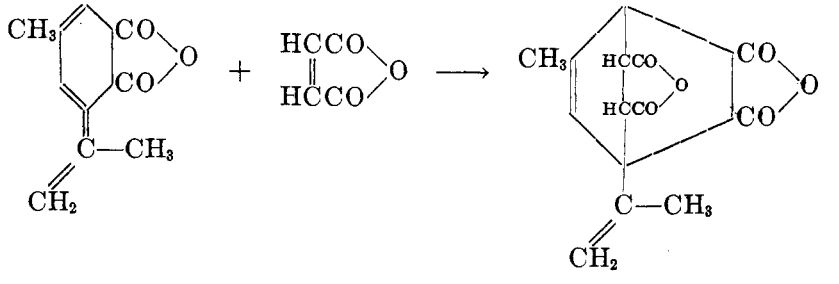


(1)

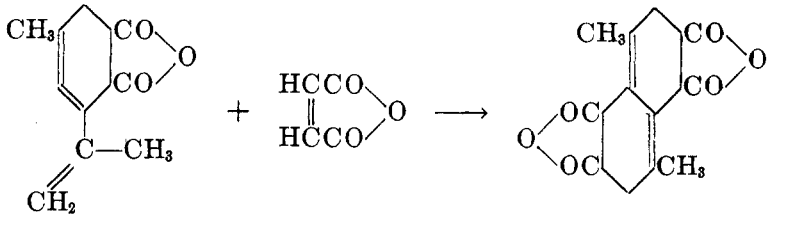


(2)

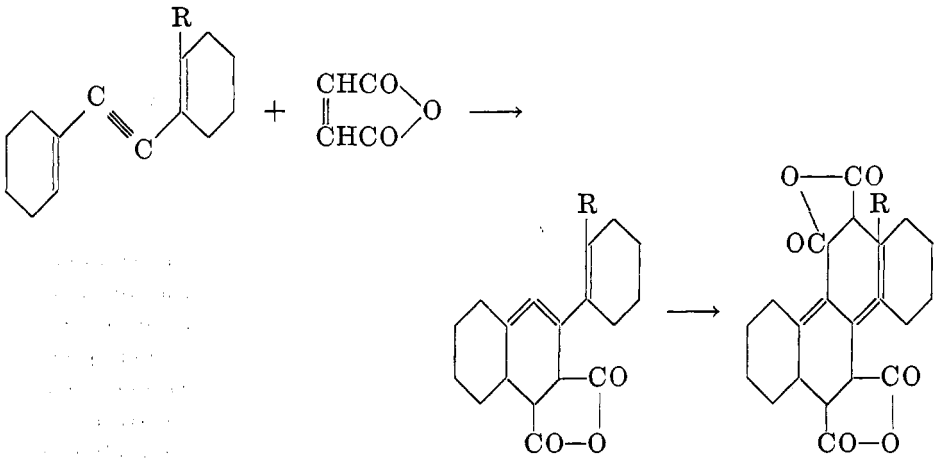
The mechanism given is that proposed by Butz; however, it seems unnecessary and indeed undesirable to postulate the isomerization of the first adduct before addition of the second mole of maleic anhydride. The author is not aware of the certainty of the locations of the double bonds in the final product as claimed by Butz. If isomerization must occur before the second mole of dienophile is added, then the substance obtained would be a mixture of the product indicated by Butz with the final product indicated immediately below:



That this conclusion is not unreasonable may be seen when it is pointed out that 1,3-cyclohexadienes are slightly more active in the diene synthesis than are open-chain dienes. If isomerization does not occur prior to addition of the second mole of maleic anhydride, the product would be that indicated below, barring subsequent isomerization:

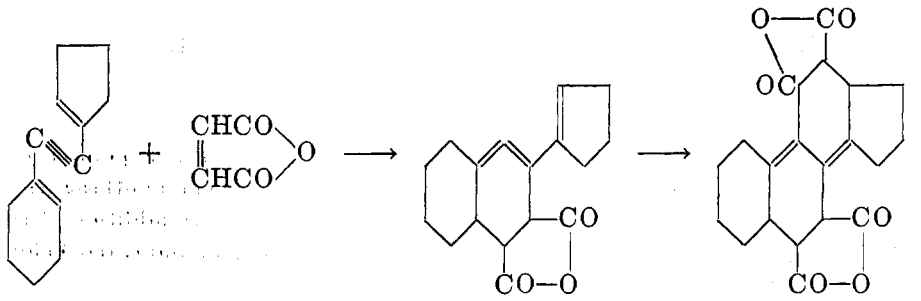


A recent paper by Joshel, Butz, and Feldman (412) describes the diene syntheses accomplished with di(1-cyclohexenyl)acetylene and 1-cyclohexenyl(2-methyl-1-cyclohexenyl)acetylene, each of which adds 2 moles of maleic anhydride. The formula of the product is given as that which might be expected if no rearrangement of double bonds occurs between the additions of the first and the second moles of maleic anhydride:



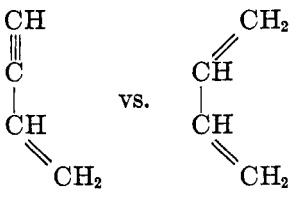
(R = H or CH_3)

Butz and Joshel (398) have been able to synthesize compounds containing the sterol-ring structure by employing 1-cyclohexenyl-1-cyclopentenylacetylene in the diene synthesis. With maleic anhydride, the reaction appears to proceed as follows:



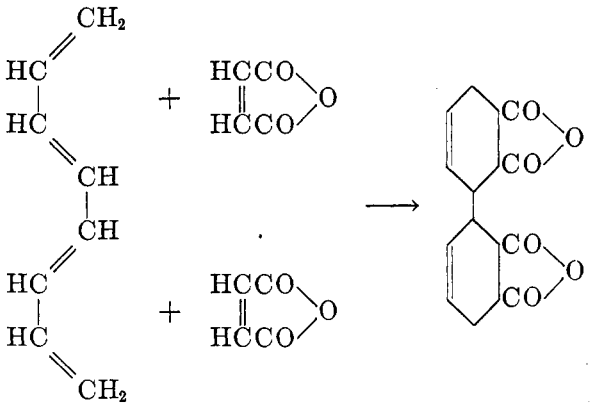
Dimethyl and diethyl fumarates have been added (399) to the above two cyclic dienynes to give adducts of structures similar to those with maleic anhydride.

The yields of adducts from these diene syntheses are not usually very high, since carbon atoms 1 and 4 of the vinylacetylene residue are further apart than in dienes. This is because acetylene is a straight-line molecule, while ethylene is more angular. In vinylacetylene and butadiene a comparison may be drawn. The inference is that proximity of carbon atoms 1 and 4 favors the diene synthesis:



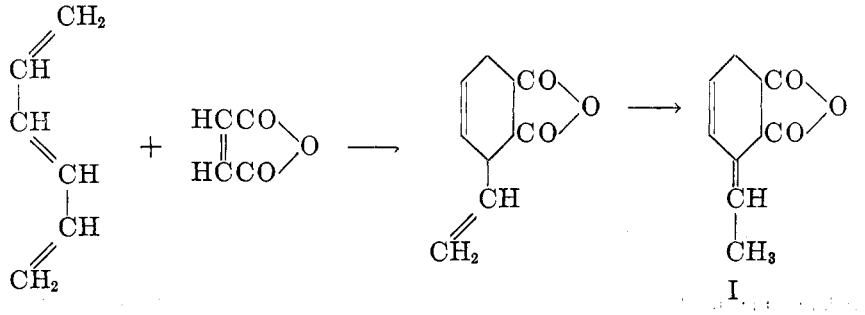
V. POLYENES

Since the conjugated polyenes possess the structure C=C—C=C, it is possible for them to add dienophiles. Further, in a triene such as hexatriene, it is of great importance to determine if the addition of a dienophile takes place at the 1,4- or 1,6-positions, or both; or in higher polyenes, to determine if addition takes place in the 1,4-, 1,6-, 1,8-, or even 1,10-positions. Indications are that, irrespective of the length of the conjugated system, addition invariably takes place at the 1,4-positions, and that each pair of conjugated double bonds in the system acts as an independent unit. Thus 1,3,5,7-octatetraene would add two mole proportions of maleic anhydride to form 1,2,3,4,1′,2′,3′,4′-octahydro-2,3,2′,3′-tetracarboxydiphenyl dianhydride:



A. Trienes, tetrenes, etc.

The simplest conjugated triene, 1,3,5-hexatriene, has been studied more thoroughly than any other polyene. It was first studied by Farmer and Warren (199), who obtained adducts with both *cis*- and *trans*-hexatrienes. They assigned structure I to the adduct obtained with maleic anhydride, the formation of which involves a rearrangement of the unattacked terminal double bond as well as the usual double-bond shift of a 1,4-addition to a conjugated



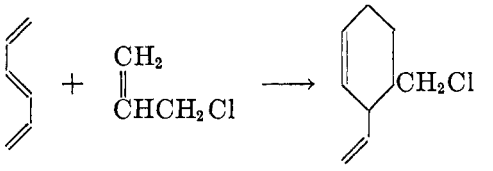
I

diene. Kharasch, Nudenberg, and Sternfeld (267) claim that the structure is not that given by Farmer and Warren, but is that of 3-vinyl-1,2,3,6-tetra-

hydrophthalic anhydride, evidence being adduced from spectroscopic data. If conditions of the addition are drastic enough to cause the double-bond shift postulated by Farmer and Warren, it would seem that they would be sufficiently drastic to cause further wandering into the ring, since in the terpenes semicyclic double bonds such as this exhibit a marked tendency to wander into the ring, particularly under the influence of acids. The resulting product is usually a conjugated cyclic diene, which adds dienophiles with great avidity. Since hexatriene adds but 1 mole of maleic anhydride, support is given the Kharasch structure. Although the Farmer and Warren adduct structure is that of a conjugated diene, it would not be expected to add maleic anhydride without a preliminary double-bond rearrangement, because of the fixed *trans*-butadienoid structure of this compound.

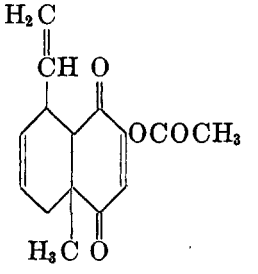
Much of the confusion may be cleared up by the discovery that the 1,3,5-hexatriene of Farmer and Warren contained cyclohexadiene (397).

Kharasch and Sternfeld (268) prepared 1,3,5-hexatriene by the reaction of allyl chloride with a solution of sodium amide in liquid ammonia. In this preparation a diene reaction was noted between hexatriene and allyl chloride:

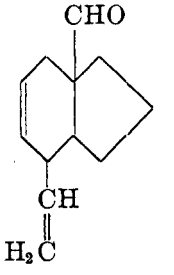


The product could have been the meta-isomer, but this was proved not to be the case. This reaction is quite unusual, for it occurs at −33°C. with a dienophile which does not possess the activating carbonyl group.

Butz and his coworkers have studied additions of other dienophiles to 1,3,5-hexatriene. α-Naphthoquinone (99) gave 1,1a,4,4a-tetrahydro-1-vinyl-9,10-anthraquinone, in agreement with Kharasch's postulates concerning the structure of the side chain of hexatriene adducts. 4-Hydroxytoluquinone acetate and 1-aldehydocyclopentene give compounds which are thought to be II and III, respectively:



II



III

In the case of II, the obvious alternative is an adduct containing an angular acetoxyl group. Presumably the facility of formation of angular groups is inversely proportional to their size. Since the methyl group is smaller than

the acetoxyl group, the angular methyl group should be formed preferentially; actually, both are formed.

The adduct with α-naphthoquinone may be oxidized by air to α-vinyl-9,10-anthraquinone. Butz (98, 99) opines that the structures given for the adducts with 4-hydroxytoluquinone acetate and with 1-formylcyclopentene are the "most probable" structures (II and III), but says that the structure assigned to III is tentative. It is certain, however, that angular groups exist in the compounds represented by II and III.

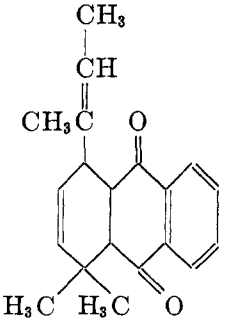
Robinson, Walker, and Todd (310) assert that 1,3,5-hexatriene does not add 1-methyl-1-cyclohexen-3-one.

Kharasch and his students (267) have extended their hexatriene synthesis to the preparation of 2,5-dimethyl-1,3,5-hexatriene, using methallyl chloride (3-chloro-2-methyl-1-propene). This adds maleic anhydride, giving the expected compound, 1,2,3,6-tetrahydro-4-methyl-6-isopropenylphthalic anhydride.

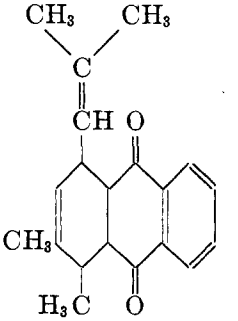
Vitamin A and related compounds, such as bixin, the carotenes, lycopene, and the xanthenes, should be capable of adding one or more moles of maleic anhydride by virtue of their long-chain conjugated systems. Kuhn and Wagner-Jauregg (273) have demonstrated addition of maleic anhydride to dyes of the bixin and carotene series. Vitamin D_2 (calciferol) is a highly substituted ring-fused hexatriene which adds maleic anhydride (368). It reacts much less readily, however, than does vitamin A (124). A separation of the vitamin D of fish-liver oils from the accompanying vitamin A and carotene (124) is based upon this fact.

Arbuzov (54, 57) has added α-naphthoquinone to alloöcimene. Though the structure of the product was not proved, evidence was secured which indicated that the structure was IV rather than V. Alloöcimene also adds crotonaldehyde and acrolein, but Arbuzov (58) neither proved the structure nor made an assumption or suggestion as to which of the four possible structures for each adduct was the correct one. The adducts appeared to be chemical individuals rather than mixtures.

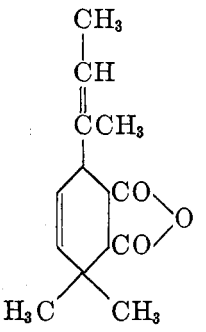
Alloöcimene adds maleic anhydride (192, 238, 407) to give a product presumed to be VI, although the alternative structure (VII) has not been disproved.



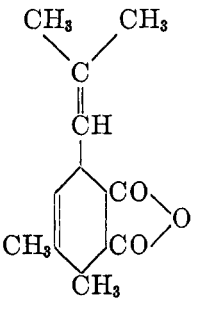
IV



V



VI



VII

Diphenylpolyenes were investigated by Diels, Alder, and Pries; also by Kuhn and Wagner-Jauregg (152, 273). 1,6-Diphenyl-1,3,5-hexatriene adds maleic anhydride in the 1- and 4-positions. 1,8-Diphenyloctatetraene adds 1 mole of maleic anhydride in boiling xylene at the 1- and 4-positions; by fusing the generators together, 2 moles of maleic anhydride were added. In boiling xylene 2 moles of maleic anhydride are added to give an isomer which yields *p*-tetraphenyl on decarboxylation and oxidation, thus showing that the second mole of maleic anhydride adds at the 5- and 8-positions. The tetraene also added 2 moles of fumaroyl chloride.

1,10-Diphenyl-1,3,5,7,9-decapentaene adds 2 moles of maleic anhydride. Decarboxylation and oxidation of the two isomeric products formed gave a material which appeared to be 1,2-bis-*p*-xenylethylene, indicating that the 2 moles of maleic anhydride had added at the 1-, 4-, 7-, and 10-positions. 1,12-Diphenyl-1,3,5,7,9,11-dodecahexaene appeared to add 3 moles of maleic anhydride; oxidation and decarboxylation of the product gave a material which appeared to be *p*-quinquephenyl. The important conclusions of the investigators were (*a*) that the diphenylpolyenes add maleic anhydride in positions which correspond with those in butadiene and (*b*) that the positions nearest the phenyl groups are the most reactive. This latter conclusion arose from the fact that degradation of the adducts from 1,10-diphenyldecapentaene appeared to give 1,2-bis-*p*-xenylethylene rather than ω-(*p*-xenyl)styrene.

B. Dienynes

Several dienynes were discussed on pages 380–382 as examples of enynes, for that particular field has not been well developed as yet. Rapid progress is being made, however. Two other dienynes have been studied,—namely, 6,9-dimethyltetradeca-5,9-dien-7-yne (92), and 4,7-di-*n*-propyldeca-3,7-dien-5-yne (100). These react with 2 moles of maleic anhydride, but the products appear to be amorphous and not well established. Referring to page 382, the ring structure of the adduct of 2,5-dimethylhexa-1,5-dien-3-yne and maleic anhydride (100) was proved by degradation to 1,5-dimethylnaphthalene.

VI. HOMOCYCLIC DIENES

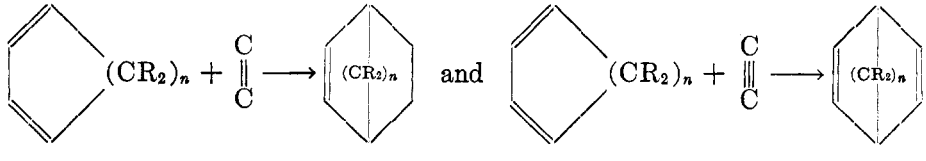
A. General

Under this heading are discussed dienes which contain their dienic double bonds in a ring composed exclusively of carbon atoms, such as cyclopentadiene and cyclopentadienone; also, compounds in which one dienic double bond is situated in a ring and the other is situated either in a side chain or else in a second ring which usually is not fused to the first ring. All rings are aliphatic in character; compounds in which one or both of the dienic double bonds are situated in a completely aromatic ring are reserved for later discussion.

1,3,5-Cyclohexatriene (benzene) has never been observed to add dienophiles, although a number of cases are known in which one of the dienic double bonds is located in a lone benzene ring and one case (9,10-anthraquinone) appears to be known in which both dienic double bonds are located in a lone benzene ring.

The first recorded addition of a dienophile to cyclopentadiene (aside from its polymerization reaction, studied by Staudinger (337) and by Bergel and Widmann (81)) was made by Albrecht (379) in 1906, using certain quinones and unsaturated ketonic compounds. Diels and Alder (136) clarified the structure of the adducts, and other illustrations of the diene synthesis with cyclic dienes were published shortly thereafter.

The general statement postulated for the diene synthesis (page 320) holds true for the homocyclic dienes, and may be written in the forms

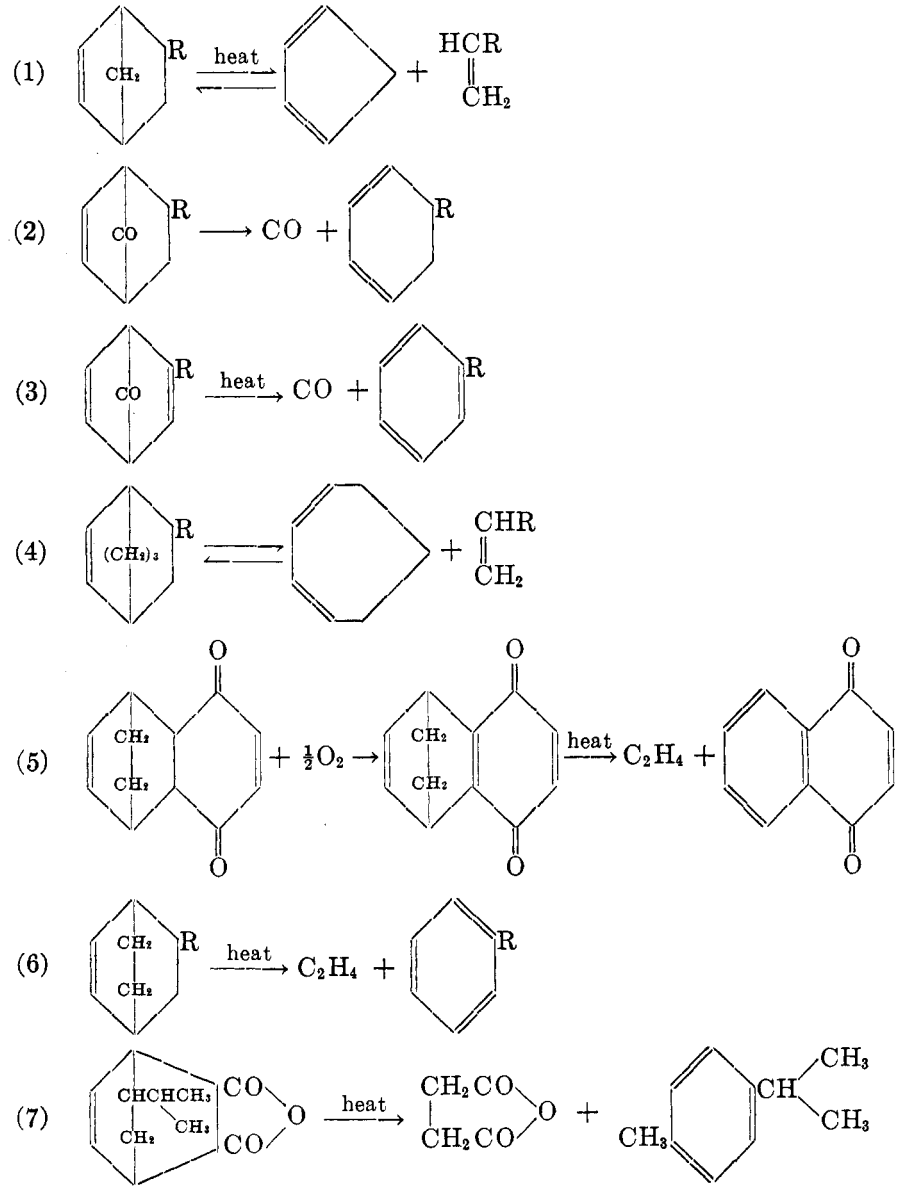


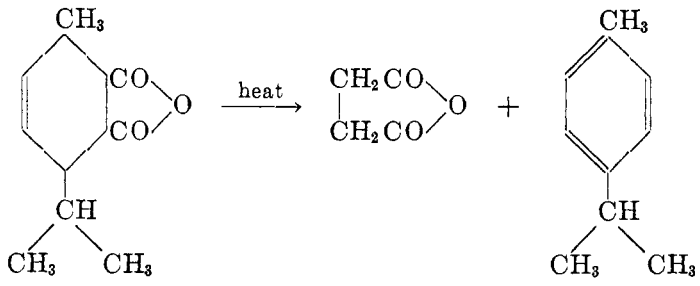
where R may be hydrogen, oxygen, or nearly any alkyl or aryl radical. Theoretically, n may be any number, but the highest value studied appears to be 3.

The adducts obtained from these cyclic dienes have a most interesting behavior on distillation at atmospheric pressure. Adducts of cyclopentadiene and its homologs either distil unchanged or else decompose into their generators. Adducts of cyclopentadienones usually evolve carbon monoxide, and the resulting product is either a benzene derivative (if derived from an acetylenic dienophile) or else a substituted cyclohexadiene which is easily oxidized to such a derivative. Occasionally the cyclohexadiene dehydrogenates spontaneously on heating (Allen). Adducts of 1,3-cycloheptadienes either distil unchanged or else decompose into their generators. The adducts of 1,3-cyclohexadienes with acetylenic dienophiles decompose on distillation to give an olefin and a benzene derivative. Fusion of adducts of cyclohexadienes and quinones in the presence of air leads to simultaneous oxidation and splitting of olefin. If a temperature is employed which is below that required to split out olefin, then oxidation occurs to give a compound which splits out olefin at the

higher temperature. The products of olefin-splitting are aromatic quinones. Dismutation of partially hydrogenated quinone adducts may be brought about by acetic anhydride in certain instances. When adducts of cyclohexadienes with olefinic dienophiles are distilled, more or less deep-seated changes occur. The usual reaction is to give a benzene derivative and the reduced dienophile. In this manner, the adducts of α-phellandrene and of 1,3-menthadiene (α-terpinene) with maleic anhydride give succinic anhydride and *p*-cymene.

Below is a summary of the reactions indicated in the preceding paragraph:



(8) 

Specific examples of the foregoing reaction types are the decomposition of the cyclohexadiene–acetylenedicarboxylic ester adduct to give ethylene and diethyl phthalate (18); the fusion of the adduct from 2 moles of cyclohexadiene and 1 mole of *p*-benzoquinone to give ethylene and 9,10-anthraquinone (34), atmospheric oxidation occurring simultaneously; the decomposition of the adduct of α-phellandrene and acetylenedicarboxylic ester to give isopropylethylene and 4-methylphthalic ester (147); and the dismutation by acetic anhydride of a partially hydrogenated adduct of cyclopentadiene with α-naphthoquinone to give α-naphthohydroquinone diacetate, cyclopentadiene, and water (which appears as acetic acid) (153).

The ethylene and carbonyl bridges are not the sole types which split out on heating, however. Lactone bridges (—CO—O—) will split out carbon dioxide on heating; this bridge is not particularly heat-stable. A good example of this reaction is found in the addition of maleic anhydride to cumalin and its derivatives, discussed elsewhere in this review. Another type is the splitting of ethylene from the partially hydrogenated adducts of certain furan derivatives with acetylenedicarboxylic ester to give dicarboxylated furan esters.

B. Cyclopentadienes

The most extensively studied of the homocyclic dienes is cyclopentadiene itself. It has been found to react with a wide variety of dienophiles, giving the anticipated products. Most of these reactions are listed in table 4; others may be found in tables 1 and 2. Polymerization reactions of the compound are discussed in a subsequent section devoted to dimerization (see page 430).

An interesting reaction of the adduct with azodicarboxylic ester is the splitting of the endomethylene bridge by hydrogen chloride to give the adduct of 1-methyl-4-chlorobutadiene and azodicarboxylic ester:

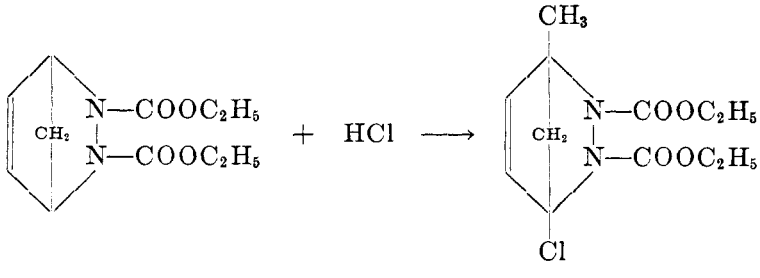


TABLE 4

Additions of dienophiles to cyclopentadiene

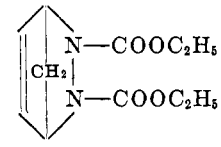
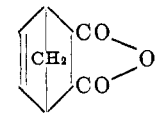
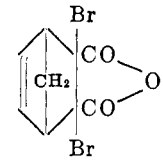
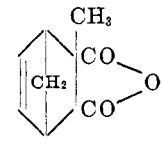
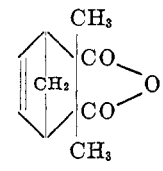
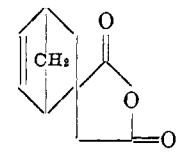
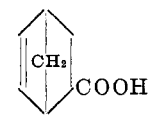
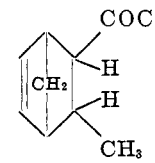
DIENOPHILE	ADDUCT	REFERENCE
Ethylene	3,6-Endomethylenecyclohexene	(411)
Azodicarboxylic ester		(157)
Maleic anhydride		(136, 137, 166)
Dibromomaleic anhydride		(151)
Citraconic anhydride		(136)
Pyrocinchonic anhydride		(146, 166)
Itaconic anhydride		(136)
Acrylic acid		(35, 37, 136)
trans-Crotonoyl chloride		(35)

TABLE 4—*Continued*

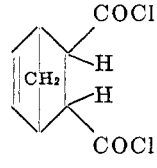
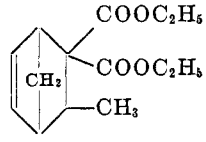
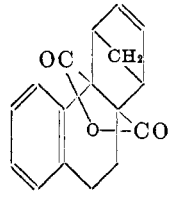
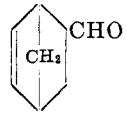
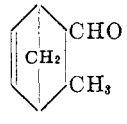
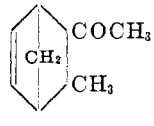
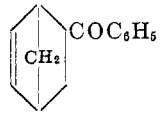
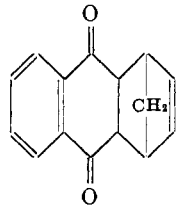
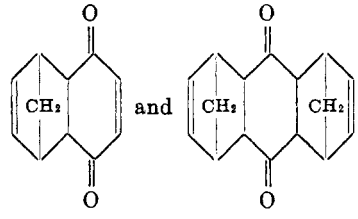
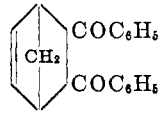
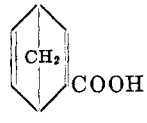
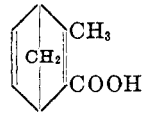
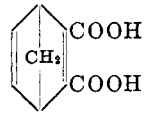
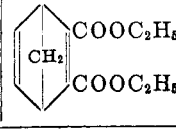
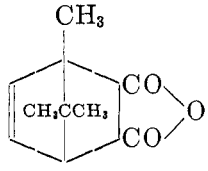
DIENOPHILE	ADDUCT	REFERENCE
Fumaroyl chloride		(35)
Ethylidenemalonic ester		(18)
1,2-Dihydro-3,4-naphthalic anhydride		(213)
Acrolein		(35, 136, 144, 150, 263)
Crotonaldehyde		(114, 150)
Ethylideneacetone		(139)
Benzoylethylene		(47)
α-Naphthoquinone		(153)

TABLE 4—*Concluded*

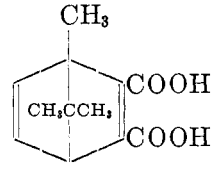
DIENOPHILE	ADDUCT	REFERENCE
p-Benzoquinone		(23, 153, 196)
cis- and *trans*-1,2-dibenzoylethylenes		(3, 6)
Propiolic acid		(39)
Tetrolic acid		(166)
Acetylenedicarboxylic acid		(147)
Acetylenedicarboxylic ester		(147)

Certain homologs and derivatives of cyclopentadiene have been investigated. Damsky (128) prepared a trimethylcyclopentadiene by distillation of the calcium salt of either α- or β-camphylic acid. Wandering of a methyl group or of a double bond (43) occurs during the pyrolysis, and the product is not 1,1,2-trimethyl-2,4-cyclopentadiene; however, it does contain a conjugated system, inasmuch as it adds vinyl acetate (44) at elevated temperatures and adds maleic anhydride and acetylenedicarboxylic ester more easily (45). If the decarboxylations of the α- and β-camphylic acids are conducted in quinoline with a copper chromate catalyst, the reactions take place at a temperature which is too low to result in isomerization of the product, and 1,1,2-trimethyl-2,4-cyclopentadiene is obtained (45). This diene is useful for the synthesis of terpinoid derivatives of bornane.

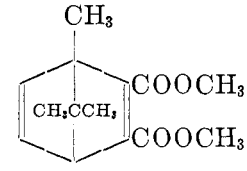
At elevated temperatures, vinyl acetate adds to 1,1,2-trimethylcyclopentadiene to give a mixture of *dl*-dehydrobornyl acetate and *dl*-dehydroepibornyl acetate. Hydrogenation, hydrolysis, and oxidation of the former adduct give *dl*-camphor. The diene also adds maleic anhydride, acetylenedicarboxylic acid, and acetylenedicarboxylic dimethyl ester to give the adducts I, II, and III:



I

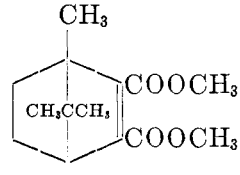


II

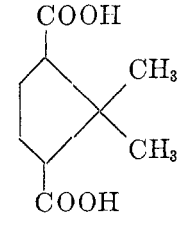


III

Adduct III may be partially reduced by platinum and hydrogen to give IV, oxidation of which by nitric acid gives a trimethylcyclopentanedicarboxylic acid (V).

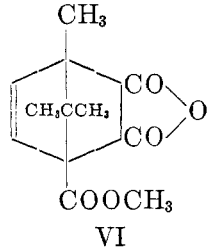


IV

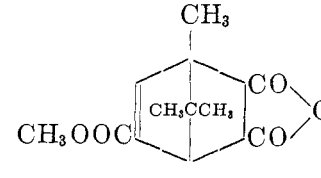


V

The camphylic acid esters add maleic anhydride, vinyl acetate, acetylenedicarboxylic acid, and acetylenedicarboxylic esters to give adducts of anticipated structures (44, 45). The maleic anhydride adducts of methyl α- and β-camphylates are VI and VII, respectively.



VI

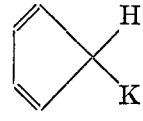


VII

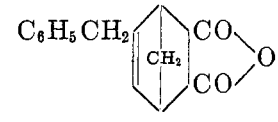
Owing to the fact that two structures are theoretically possible through the use of vinyl acetate as a dienophile, the structures of the vinyl acetate addition products are not certain.

Potassium powder, suspended in benzene or other suitable medium, reacts with cyclopentadiene to give potassium cyclopentadiene, presumably VIII.

This reacts with benzyl chloride to give a mixture of the 2- and 3-benzylcyclopentadienes, which react with maleic anhydride to give the expected adducts (12, 13). Oxidation of the adduct derived from the 3-benzyl isomer (IX)



VIII



IX

gives benzoic acid and *cis*-,*cis*-,*cis*-,*cis*-1,2,3,4-cyclopentanetetracarboxylic acid (21).

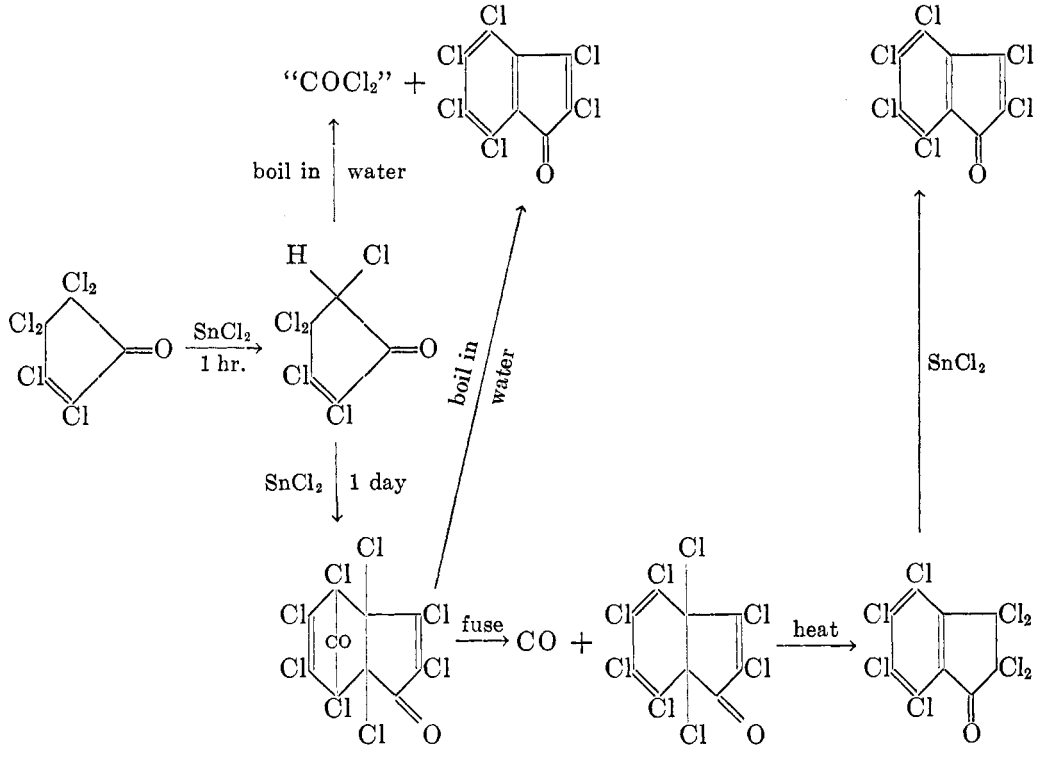
C. Cyclopentadienones

Of particular interest are the reactions of the phenyl- and chloro-substituted cyclopentadienones, for these combine the structures of reactive diene and reactive dienophile. The simpler members of the series are so reactive that they have not been isolated in the monomeric state, although their transitory existence may be demonstrated. The higher members of the series are still highly reactive, adding such inert dienophiles as acetylene, butadiene, benzonitrile, and acenaphthylene. Those cyclopentadienones with phenyl groups substituted on the 1- and 4-positions of the butadienoid system of cyclopentadienone do not dimerize, probably because of the stereochemical difficulties involved. These compounds are a fine example of the fact that the carbonyl group will enhance the reactivity of a diene as well as that of a dienophile.

The first of these cyclopentadienones to be investigated was tetrachlorocyclopentadienone, by T. Zincke and his collaborators in the period 1893–1912 (376, 377, 378). It was first observed that hexachlorocyclopenten-3-one was reducible to 1,2,4,5,5-pentachlorocyclopenten-3-one by stannous chloride during the course of 1 hr. When boiled with water, this substance lost hydrogen chloride to form tetrachlorocyclopentadienone; this compound dimerized immediately to a compound which lost the elements of phosgene (apparently the phosgene was hydrolyzed by water to carbon dioxide and hydrogen chloride) and formed hexachloroindone. It was found later that prolonged reduction (one to two days) of hexachlorocyclopenten-3-one by stannous chloride at room temperature gave the dimer of tetrachlorocyclopentadienone. The stannous chloride probably served no useful function after the initial reduction; mere standing in water was no doubt sufficient for the tetrachlorocyclopentadienone to form and dimerize. Boiling the dimer with water gave hexachloroindone, carbon dioxide, and hydrogen chloride.

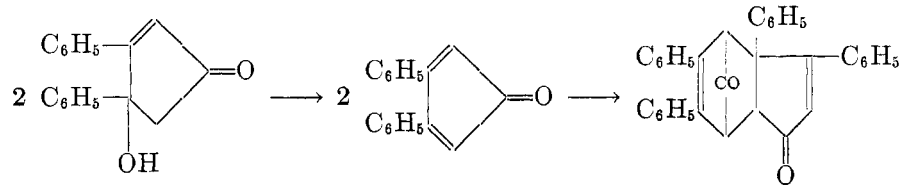
In 1912 it was found that phosgene was not liberated as such. It was shown that the dimer of tetrachlorocyclopentadienone loses carbon monoxide at its melting point to form an octachlorodihydroindone, and that further heating causes double-bond rearrangement to octachlorohydrindone. This is easily

reduced by stannous chloride to give hexachloroindone. Hence the formation of hexachloroindone by boiling the dimer of tetrachlorocyclopentadienone with water is due, in part at least, to reduction of octachlorohydrindone by carbon monoxide or one of its immediate precursors. The various reactions are shown below diagrammatically:

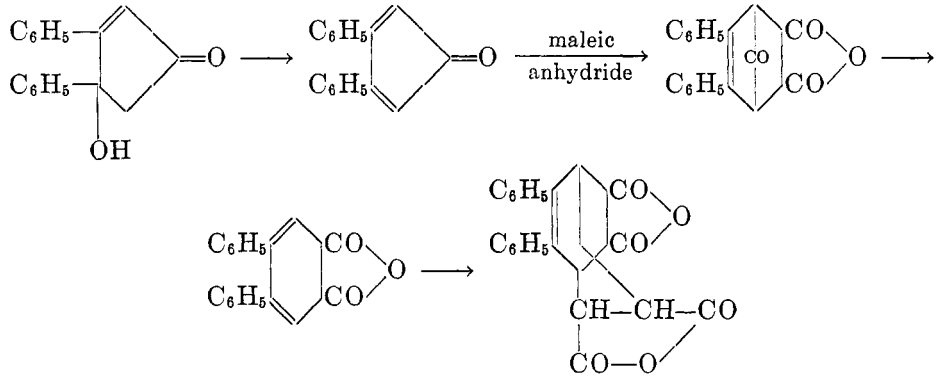


The phenylated 2,4-cyclopentadienones which have been studied include 3,4-diphenyl-, 2,3,4-triphenyl-, 2,3,5-triphenyl-, and 2,3,4,5-tetraphenyl-cyclopentadienones. The last named is also known as tetracyclone. Allied to these purely phenyl-substituted cyclopentadienones are 2,5-diphenyl-3,4-(*o*,*o'*-biphenylene)cyclopentadienone (phencyclone), and 2,5-diphenyl-3,4-(peri-naphthylene)cyclopentadienone (acecyclone). None of the 2,5-diphenylated compounds dimerizes even under extreme conditions of temperature. It is possible, therefore, to obtain all but the first two cyclopentadienones listed above in the monomeric state. These monomers are all highly colored substances.

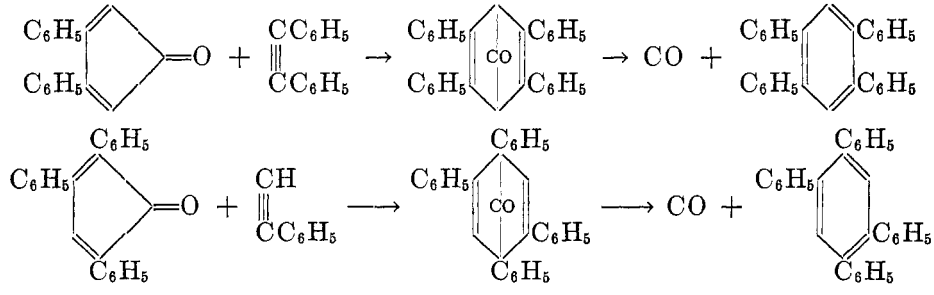
3,4-Diphenylcyclopentadienone is formed from anhydracetonebenzil in several ways (50, 51), one being by dehydration with acid. It enjoys only a transitory existence, however, dimerizing almost immediately under the conditions employed:



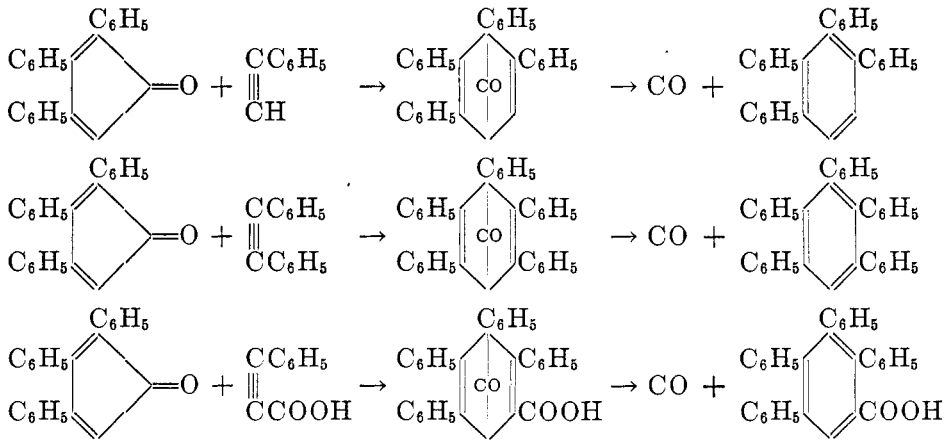
By using a large excess of maleic anhydride as the dehydrating agent, the existence of the monomeric form of 3,4-diphenylcyclopentadienone may be shown (52) by the formation of considerable quantities of an adduct derived from maleic anhydride and the monomer:



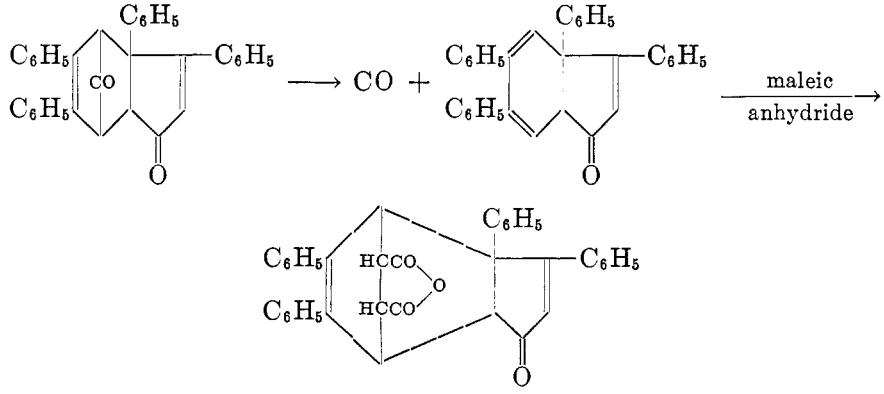
In similar fashion (178), the heating of a mixture of anhydracetonebenzil with diphenylacetylene will yield a small amount of 1,2,4,5-tetraphenylbenzene, together with much 3,4-diphenylcyclopentadienone dimer and its pyrolysis products. The same product, 1,2,4,5-tetraphenylbenzene, may be obtained in quantitative yield by the reaction of 2,3,5-triphenylcyclopentadienone (178) with phenylacetylene. The other product which is theoretically possible (1,2,3,5-tetraphenylbenzene) is not produced:



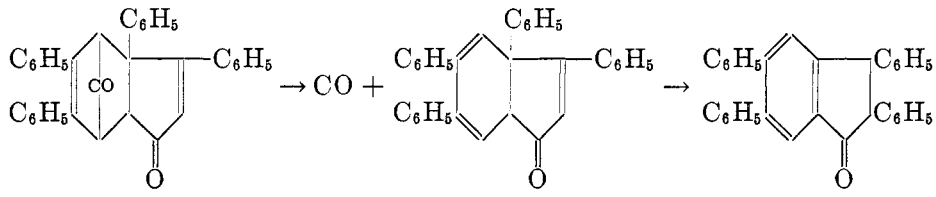
2,3,4-Triphenylcyclopentadienone is not known in the monomeric state, and dimerizes almost on formation. As in the case of 3,4-diphenylcyclopentadienone, its transitory existence may be shown by heating triphenylcyclopentenolone with phenylacetylene, phenylpropiolic acid, or diphenylacetylene. The products formed with these three dienophiles are 1,2,3,4-tetraphenylbenzene, 2,3,4,5-tetraphenylbenzoic acid, and pentaphenylbenzene, respectively (178):



It will be noted that loss of the endocarbonyl bridge occurs in each of the above syntheses. With acetylenic dienophiles this is especially true, the resulting carbonyl bridge being highly unstable toward heat. This is true to a lesser degree with the endoethylene and endolactone bridges. In the above cases, the instability of the carbonyl bridge is so great that these intermediates usually cannot be isolated. When the dienophile is an acid, the endocarbonyl compound can sometimes be obtained. Room-temperature dimerization of those cyclopentadienones which are capable of dimerization likewise gives endocarbonyl compounds. In this fashion the dimer of 3,4-diphenylcyclopentadienone loses carbon monoxide at about 230°C. to give 1,5,6,9-tetraphenyl-9,10-dihydroindone (52) and carbon monoxide. If maleic anhydride is present, an adduct is formed with this cyclohexadiene derivative:



In the absence of maleic anhydride, continued heating of 1,5,6,9-tetraphenyl-9,10-dihydroindone at 250°C. results in rearrangement to 1,2,5,6-tetraphenylhydrindone. Care is required, therefore, for success in isolating the isomeric 9,10-dihydro compound, for heating at 230°C. for any considerable length of time will also result in extensive rearrangement (52):

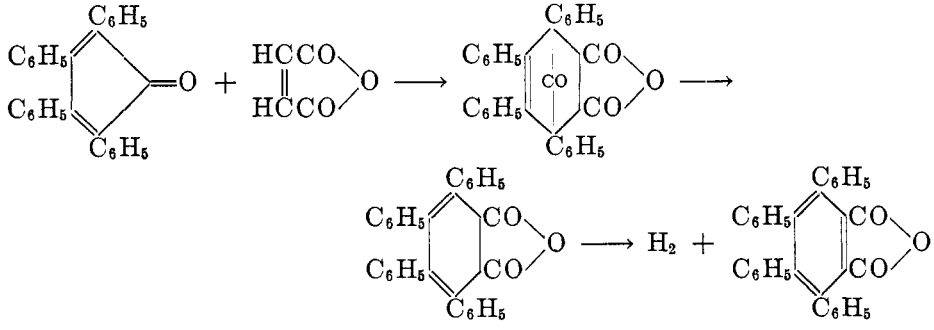


This rearrangement is analogous to that observed by Zincke (*vide supra*). The structure of the final product was confirmed by degradation to *o*-terphenyl. By heating the 9,10-dihydro compound with sulfur, 1,5,6-triphenylindene and thiophenol were formed (52). This is one of the few cases on record in which an angular aryl group is removed by sulfur dehydrogenation.

Tetracyclone (2,3,4,5-tetraphenylcyclopentadienone) was first prepared by Ziegler and Schnell (374) and almost simultaneously by Loewenbein and Ulich (287). It is a highly colored compound (red), as are all the monomeric arylated cyclopentadienones. Dilthey (180) prepared the compound by reaction of benzil with dibenzylketone to give a diphenylanhydracetonebenzil which could be dehydrated easily to tetracyclone. By substituting phenanthrenequinone or acenaphthalenequinone for benzil, one obtains phencyclone or acecylone (180).

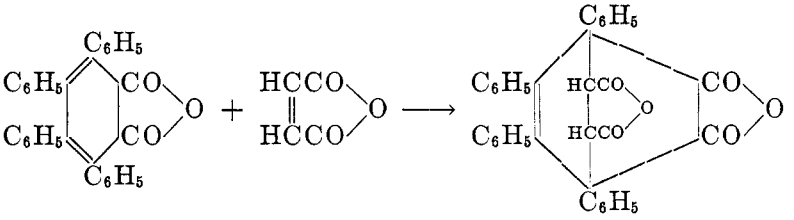
Tetracyclone is a very reactive dienic compound, though it does not dimerize. It not only adds comparatively unreactive dienophiles with ease, but it reacts with unsaturated substances which are not ordinarly thought of as dienophiles. Accordingly, it reacts with benzonitrile, liberating carbon monoxide and forming pentaphenylpyridine (181). A reaction is also shown with sulfur, the reaction products being carbon monoxide and thionessal (tetraphenylthiophene); a similar reaction is shown by 2-(*p*-anisyl)-3,4,5-triphenylcyclopentadienone, which gives carbon monoxide and the corresponding *p*-methoxythionessal (181; see also J. prakt. Chem. [2] **151**, 185 (1938)).

Maleic anhydride adds to tetracyclone, and here the various intermediates may be isolated. The first product is 3,6-endocarbonyl-1,2,3,6-tetrahydro-3,4,5,6-tetraphenylphthalic anhydride; at higher temperatures this loses carbon monoxide to form 3,4,5,6-tetraphenyl-1,2-dihydrophthalic acid. At still higher temperatures, hydrogen is evolved and 3,4,5,6-tetraphenylphthalic acid is formed (49, 51, 182, 184):



The conversion of the dihydro acid to tetraphenylphthalic acid is best accomplished by use of a dehydrogenating agent, such as sulfur, or by using an oxidizing

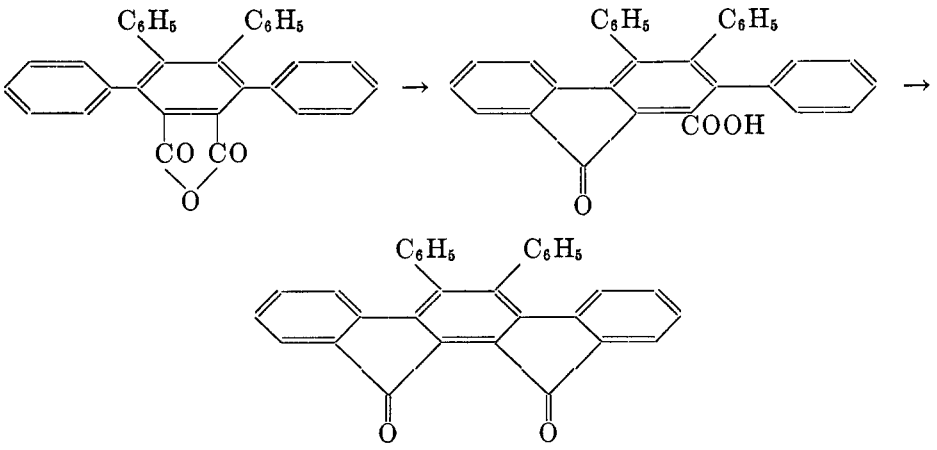
solvent (nitrobenzene) for the reaction mixture. If the formation of tetraphthalic acid is carried out in one step from tetracyclone and maleic anhydride, the final product contains small amounts of the adduct of maleic anhydride with the dihydrophthalic acid:



A considerable number of other dienophiles has been added to tetracyclone. Indeed, this compound has been the most thoroughly studied of the cyclopentadienones with regard to activity in the diene synthesis. Benzalacetophenone was reported (49) not to add to tetracyclone, but it was shown later that addition would occur under forcing conditions (47), the products being carbon monoxide and 2,3,4,5,6-pentaphenylbenzophenone. Acetylene is added, even at 100°C., to give carbon monoxide and 1,2,3,4-tetraphenylbenzene (182). Phenylacetylene gives carbon monoxide and pentaphenylbenzene (182), and stilbene gives hydrogen, carbon monoxide, and hexaphenylbenzene of melting point 426°C. (182). The same product was obtained without evolution of hydrogen by the use of diphenylacetylene in place of stilbene (178, 181, 182). The melting point of the hexaphenylbenzene thus obtained was nearly 200°C. higher than that reported previously in the literature, which corresponded more closely with that of 1,2,4,5-tetraphenylbenzene. The previous preparation was made by the interaction of phenylmagnesium bromide with hexachlorobenzene; duplication of this work gave a similar compound (177). Molecular-weight determinations showed that the previously reported hexaphenylbenzene was in reality a tetraphenylbenzene, while the compound produced by the addition of diphenylacetylene or stilbene to tetracyclone had an observed molecular weight agreeing with the theoretical value for hexaphenylbenzene. It has an uncorrected melting point of 426°C. The previous report of the synthesis of hexaphenylbenzene must be regarded as an error.

Diphenylbutadiyne (181) also adds to tetracyclone with evolution of carbon monoxide and the product is (pentaphenylphenyl)phenylacetylene. Further reaction, which would produce decaphenylbiphenyl, does not appear to occur. With butadiene (181), such double addition does occur; carbon monoxide is evolved and the product is a mixture of octaphenylbiphenyl with various hydrogenated octaphenylbiphenyls. Cyclohexene adds in a forced reaction (181), giving carbon monoxide, hydrogen, and *Bz*-tetraphenyltetralin. Phenylbromoacetylene (181) adds easily to give pentaphenylbromobenzene. Acenaphthylene (176) gives 2,3,4,5-tetraphenyl-1,6-(peri-naphthylene)benzene. Benzoylethylene (47) adds, with evolution of carbon monoxide and hydrogen, to give 2,3,4,5-tetraphenylbenzophenone. Phenylpropiolic aldehyde (182) gives carbon monoxide and pentaphenylbenzaldehyde, and phenylpropiolic nitrile gives carbon monoxide and pentaphenylbenzonitrile.

The additions of unsaturated dibasic acids and certain of their esters to tetracyclone often result in products which contain the carbonyl bridge. The bridge can be removed by further heating and finally an aromatic acid or ester may be formed. This was shown to be the case in the addition of maleic anhydride to tetracyclone. True adducts containing the carbonyl bridge are rarely isolable in other cases. Of the dienophiles mentioned above, none undergoes reaction at temperatures lower than the temperatures required for complete decomposition of their adducts, save for maleic anhydride. Additions of the methyl and ethyl esters of acetylenedicarboxylic acid require too high a temperature to allow isolation of such intermediates (49, 184), and the products are methyl and ethyl tetraphenylphthalates. The same products are obtainable from the corresponding esters of maleic acid. While no endocarbonyl intermediate can be obtained with dimethyl maleate, such may be obtained with diethyl maleate and with dimethyl fumarate (49), because the temperatures required for reaction with the latter two esters are lower than the decomposition temperatures of the adducts resulting from such addition. Strong heating of these adducts also gives tetraphenylphthalic esters. These esters, being derived from hindered aromatic acids, are difficult to hydrolyze (49), and the ethyl ester of tetraphenylphthalic acid is stable to molten alkali at 360°C. The corresponding acid anhydride, from tetracyclone and maleic anhydride or acetylenedicarboxylic acid, condenses to a fluorenone on treatment with aluminum chloride in boiling benzene (184); more drastic treatment gives a difluorenone.



Phenylpropiolic methyl ester (184) requires a high temperature for addition to tetracyclone; consequently the intermediate carbonyl-bridged adduct is not obtainable. The corresponding acid (182, 184) also requires a high temperature for addition; it yields pentaphenylbenzoic acid. This latter acid can be condensed (184) with aluminum chloride to give 1,2,3,4-tetraphenylfluorenone. Tetrolic acid or its ethyl ester (184) gives tetraphenyl-*o*-toluic acid or its ester.

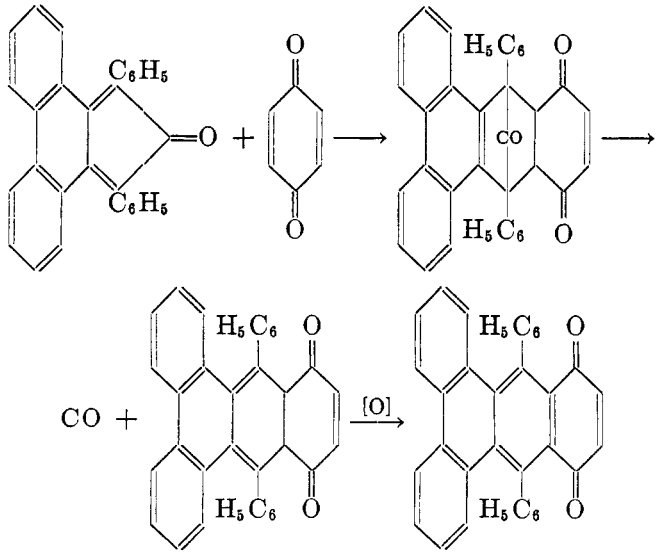
Diphenylketene does not react (49) with tetracyclone. This supports Staudinger's hypothesis (81) that diphenylketene undergoes 1,2-addition to conjugated and isolated double bonds. Quinones appear not to have been

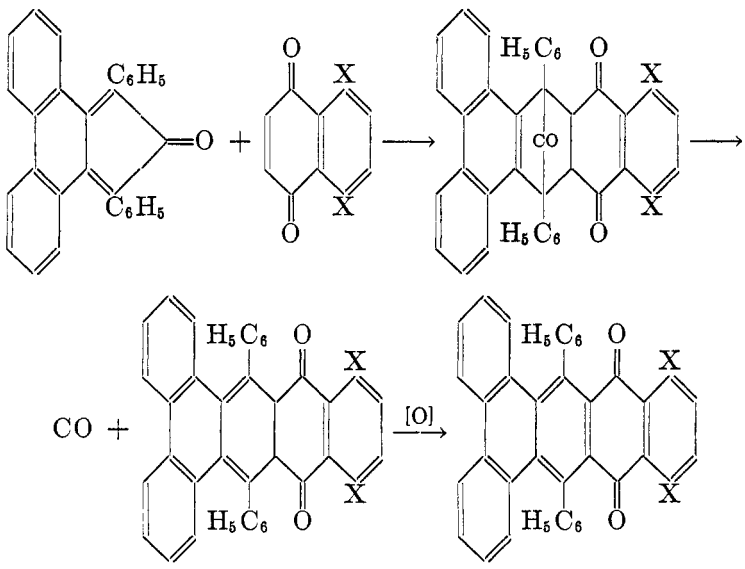
investigated, at least with tetracyclone, but the fact that adducts containing endocarbonyl bridges may be prepared with phencyclone and quinones lends support to the prediction that such will also be found to be the case with tetracyclone.

Grummitt and coworkers (408) report that tetracyclone adds a mole of cyclopentadiene to give a carbonyl-bridged adduct. In attempting to remove the carbonyl bridge by heating, preferential dissociation took place to give the original generators. No reaction was noted between tetracyclone and furan, pyrrole, *N*-methylpyrrole, or thiophene.

Allen and van Allan (387) describe 2,5-dimethyl-3,4-diphenylcyclopentadienone as being midway between 3,4-diphenylcyclopentadienone and tetracyclone. This substance is not known in the monomeric form, but in solution its dimer reacts as if it were monomeric. This dissociation of the dimer should be compared with 3,4-diphenylcyclopentadienone, which dimerizes completely and permanently, and with tetracyclone, which does not dimerize at all. Thus, the dimer of 2,5-dimethyl-3,4-diphenylcyclopentadienone will add acetylene, phenylacetylene, β-nitrostyrene, vinyl phenyl ketone, maleic anhydride, and other dienophiles because of the preliminary dissociation to the monomeric form.

Phencyclone (180) reacts with *p*-benzoquinone, naphthoquinone, naphthazarin, and naphthazarin diacetate to give adducts containing carbonyl bridges. Heating to elevated temperatures causes loss of carbon monoxide, and dihydroquinones are formed which may be dehydrogenated by atmospheric oxygen or other dehydrogenating agents to give fully aromatic quinones. In order to isolate these intermediates, it is essential that one operate in an inert atmosphere (carbon dioxide). *p*-Benzoquinone finally gives 1,2,3,4-dibenz-9,10-diphenyl-5,8-anthraquinone; α-naphthoquinone gives 1,2,3,4,6,7-tribenz-9,10-diphenyl-5,8-anthraquinone; and naphthazarin or its diacetate gives 1,4-diphenyl-2,3-(*o*,*o*′-biphenylene)-5,8-dihydroxy-9,10-anthraquinone or its diacetate:



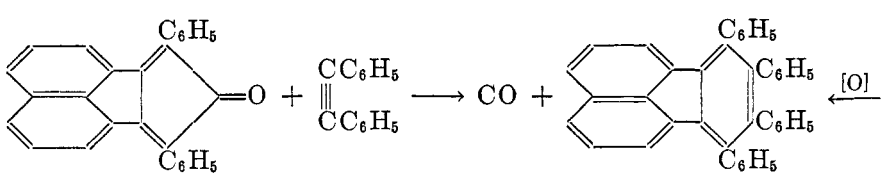


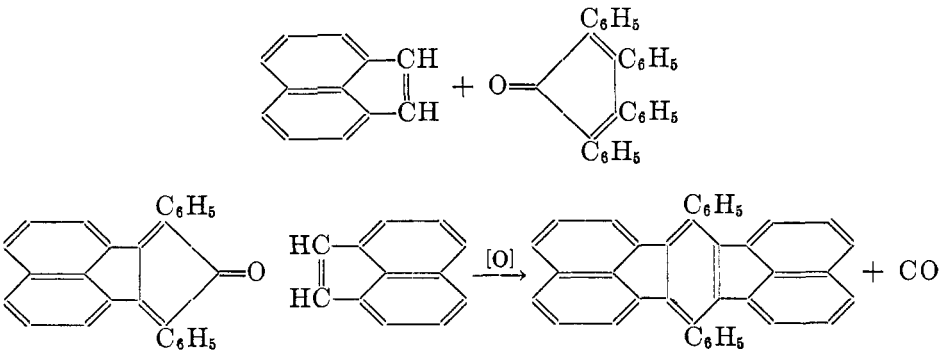
(X = hydrogen, hydroxyl, or acetoxyl)

Reduction of these quinones from *p*-benzoquinone and from α-naphthoquinone would give the corresponding hydrocarbons. It can be seen, therefore, that this method offers means of preparing diphenylated dibenzanthracenes and naphthacenes and related hydrocarbons, some of which may be carcinogenic.

Phencyclone has been added to fumaric acid, maleic acid, and maleic anhydride (183), phenylpropiolic acid (176), phenylacetylene (176), diphenylacetylene (176), and benzoylethylene (47) to give products corresponding with those obtained from tetracyclone. It also reacts with sulfur, but the reaction is more complex than that with tetracyclone; the product is of more or less indefinite composition, for the amount of sulfur utilized ranges between four and five atoms per molecule of phencyclone. When distilled, this sulfurized product affords a 20 per cent yield of biphenylenediphenylthiophene, there being evolved carbon dioxide, carbon monoxide, carbon oxysulfide, and hydrogen sulfide.

Acecyclone shows no reaction whatever with sulfur. It has been shown to add benzoylethylene (47), acetylene (176), and phenylacetylene (176); the structures of the products correspond with those of the tetracyclone series. The adduct with diphenylacetylene (176) is identical with the adduct obtained from tetracyclone and acenaphthylene; acecyclone also adds acenaphthylene to give carbon monoxide and 1,4-diphenyl-2,3,5,6-bis(peri-naphthylene)benzene (176):

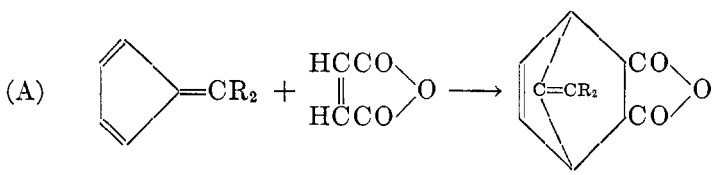


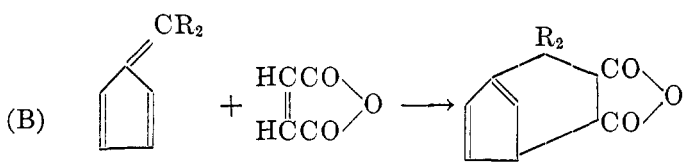


Benzalacetophenone, diphenylketone, and 1,2-dibenzoylethylene could not be added to either phencyclone or acecyclone (49).

D. Fulvenes

Fulvenes are the 1-alkylidenecyclopentadienes, and contain one more double bond than cyclopentadiene. This double bond is conjugated with each of the two double bonds of the cyclopentadiene ring, and at first sight one might think that ambiguity might arise in determining which of the two possible routes (A or B) might be followed by the addition of dienophiles to fulvenes:





The fact that the postulated addition represented by reaction B would occur through addition to a *trans*-butadienoid system (see page 323) and that addition A would occur through addition to a *cis*-butadienoid system strongly suggests that addition A occurs rather than B. Further, the hypothetical reaction product of B possesses a 1,3-cyclopentadiene ring and therefore should be capable of adding a second mole of dienophile. Only 1 mole of dienophile adds to the fulvenes.

An outstanding characteristic of fulvene adducts is the fact that they are usually dissociated to a greater or less extent when in solution, though stable in the solid state. The extent of dissociation can be estimated colorimetrically in many cases, since the sole colored material in the equilibrium mixture is the fulvene (270). Oftentimes molecular-weight determinations are employed for estimation of the degree of dissociation of these adducts. Equilibrium is at-

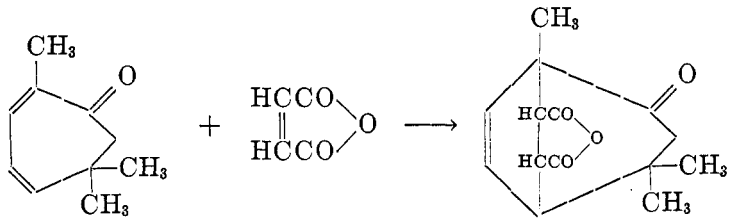
tained slowly in these solutions, as may be shown by the gradual increase in color of a solution of a fulvene adduct on standing.

Dimethylfulvene and diphenylfulvene react with maleic anhydride to give adducts which dissociate in solution, as do the maleic anhydride adducts of tetra- and penta-methylenefulvenes (which are prepared from cyclopentadiene and cyclopentanone or cyclohexanone (27, 270)). An interesting case is that of β-styrylfulvene (270), which contains both the fulvene and straight-chain butadiene structures: $C_6H_5CH{=}CH{-}CH{=}C(=C_4H_4)$. This compound could add maleic anhydride across either the cyclopentadiene ring or the butadienyl side chain, or both. Circumstantial evidence indicates that addition occurs across the ring, for the maleic anhydride adduct is dissociated in solution (270). A more stable adduct, which would involve the butadiene structure, might be formed at elevated temperatures. Formation of such an adduct appears to have been neither attempted nor reported.

E. Cyclohexadienes and cycloheptadienes

The liberation of an olefin and simultaneous formation of a benzene derivative on pyrolysis of adducts of acetylenic dienophiles with cyclohexadienes serves to distinguish cyclohexadienes from cyclopentadienes and cycloheptadienes (13). The test is not conclusive unless it is shown that both the olefin and the benzene derivative are formed, since the partially reduced adducts of acetylenedicarboxylic ester with furan or sylvan (2-methylfuran) and also the decarboxylated adduct of anthraquinone and maleic anhydride evolve ethylene on pyrolysis (14, 153). This property of evolution of olefins and formation of a benzene derivative is perhaps the most important chemical property of adducts of cyclohexadienes.

Cycloheptadiene adds acetylenedicarboxylic esters (14, 33) to give esters of 3,6-endopropylene-3,6-dihydrophthalic acid, which are either stable to heat or else decompose into their generators. Eucarvone (33, 357) is a cycloheptadienone; it adds maleic anhydride as follows:



Eucarvone

Cyclohexadiene additions have been rather well studied, though not as thoroughly as cyclopentadiene additions. Certain terpadienes, such as α-phellandrene, are conjugated cyclohexadienes. The decomposition of their acetylenedicarboxylic ester adducts to easily identified olefins and esters of phthalic acid and its homologs affords a convenient general method for structure determination of the original cyclohexadiene.

TABLE 5

Cyclohexadienes in the diene synthesis

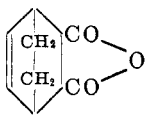
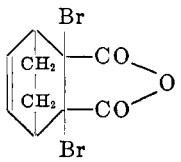
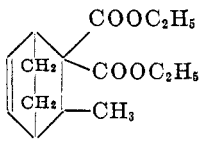
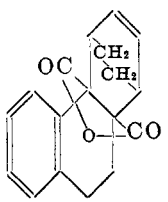
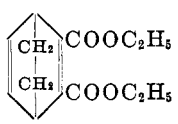
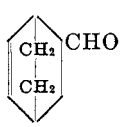
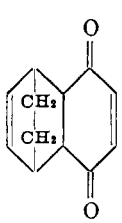
DIENE	DIENOPHILE	PRODUCT	REFERENCE
Cyclohexadiene....	Maleic anhydride		(136, 146, 199)
Cyclohexadiene....	Dibromomaleic anhydride		(151)
Cyclohexadiene....	Ethylidenemalonic ester		(18)
Cyclohexadiene....	1,2-Dihydro-3,4-naphthalic anhydride		(213)
Cyclohexadiene....	Acetylenedicarboxylic diethyl ester		(13, 14, 147)
Cyclohexadiene....	Acrolein		(151)
Cyclohexadiene....	Benzoylethylene	No reaction	(47)
Cyclohexadiene....	*p*-Benzoquinone		(23, 153)

TABLE 5—*Continued*

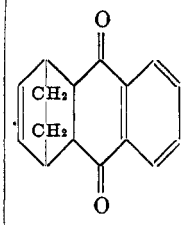
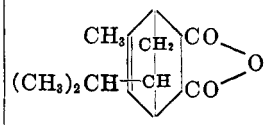
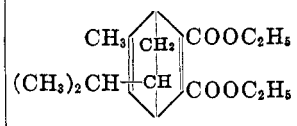
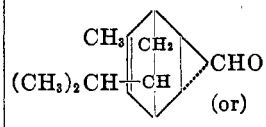
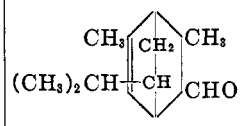
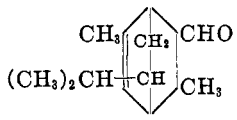
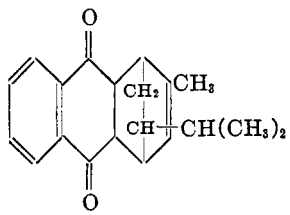
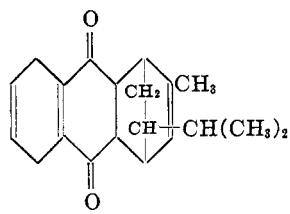
DIENE	DIENOPHILE	PRODUCT	REFERENCE
Cyclohexadiene....	α-Naphthoquinone		(153)
α-Phellandrene	Maleic anhydride		(136, 418)
α-Phellandrene	Acetylenedicarboxylic diethyl ester		(13)
α-Phellandrene	Acrolein	 (or)	(144)
α-Phellandrene	Crotonaldehyde	 or 	(144)
α-Phellandrene	Benzoylethylene	"A hopeless mass"	(47)
α-Phellandrene	α-Naphthoquinone		(153)
α-Phellandrene	5,8-Dihydro-1,4-naphthoquinone		(135)

TABLE 5—*Continued*

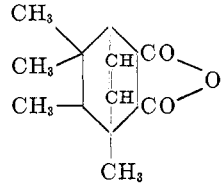
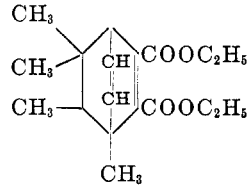
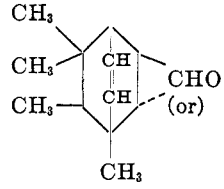
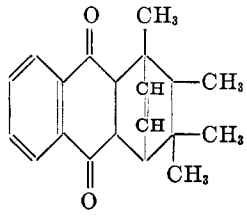
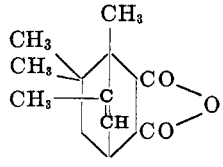
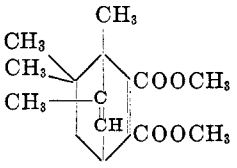
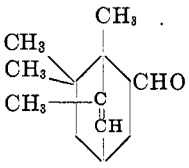
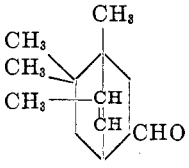
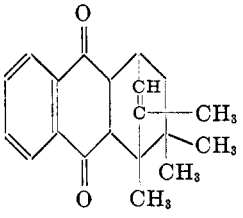
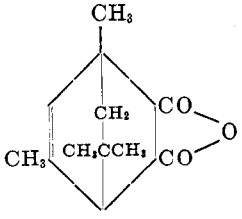
DIENE	DIENOPHILE	PRODUCT	REFERENCE
α-Pyronene.....	Maleic anhydride		(190, 238, 407)
α-Pyronene.....	Acetylenedicarboxylic dimethyl ester		(191)
α-Pyronene.....	Acrolein		(190)
α-Pyronene.....	Dibenzoylacetylene	No reaction	(191)
α-Pyronene.....	*p*-Benzoquinone	No reaction	(191)
α-Pyronene.....	α-Naphthoquinone		(191)
β-Pyronene.....	Maleic anhydride		(190, 407)

TABLE 5—*Concluded*

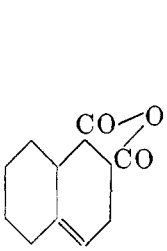
DIENE	DIENOPHILE	PRODUCT	REFERENCE
β-Pyronene.....	Acetylenedicarboxylic methyl ester		(191)
β-Pyronene.....	Acrolein	 (or) 	(190)
β-Pyronene.....	Dibenzoylacetylene	No reaction	(191)
β-Pyronene.....	*p*-Benzoquinone	No reaction	(191)
β-Pyronene.....	α-Naphthoquinone		(191)
1,3,5,5,-Tetramethylcyclohexadiene.....	Maleic anhydride		(413)

β-Phellandrene, though not a cyclohexadiene, is isomeric with α-phellandrene, and differs from the latter only in double-bond arrangement. One of these double bonds is semicyclic and is conjugated with the other. Refluxing with

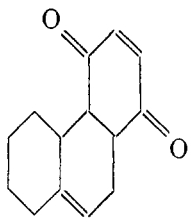
maleic anhydride (228) gives a resinous reaction product, high-vacuum distillation of which affords an 8 per cent yield of the adduct of α-phellandrene and maleic anhydride. This adduct could be detected only as the result of distillation and probably is formed on pyrolysis of the resin rather than by any direct interaction of maleic anhydride and β-phellandrene. This indicates that normal diene syntheses to *trans*-butadienoidal configurations do not occur without rearrangement, and is evidence for the rule given on page 323.

F. "Semicyclic" and dicyclic dienes

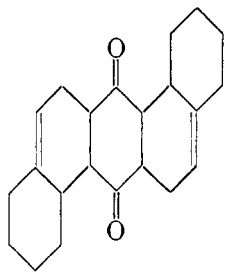
These include dienes such as 1-vinylcyclopentene and bis-1-cyclohexenyl. Of the first type, 1-vinylcyclohexene itself has been shown (126) to add maleic anhydride to give 1,2,3,5,6,7,8,8a-octahydro-1,2-naphthalic anhydride (IX) and to add *p*-benzoquinone to give 5,6,7,8,10,1a,4a,5a-octahydro-1,4-phenanthrenequinone (X) and also 1,1a,4,4a,5,5a,8,8a-*Bz*-(1,2,3,4)-*Bz'*-(1,2,3,4)-hexadecahydro-1,2,5,6-dibenz-9,10-anthraquinone (XI):



IX

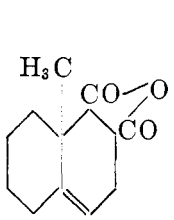


X

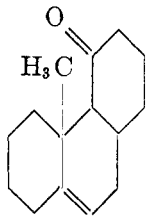


XI

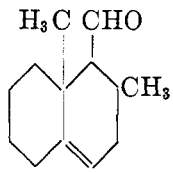
That these types of dienes are quite active is shown by the fact that 1-vinyl-2-methylcyclohexene adds maleic anhydride, cyclohexen-3-one, and crotonaldehyde (293) to give adducts XII, XIII, and XIV, respectively, all of which contain angular methyl groups.



XII

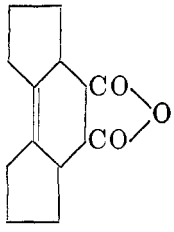


XIII

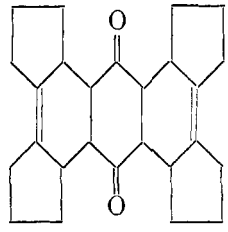


XIV

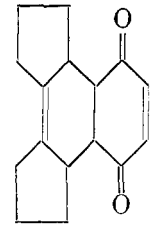
Bis-1,1'-cyclopentenyl (74) adds maleic anhydride to give the dicarboxylic acid (XV). In boiling methanol, *p*-benzoquinone adds 1 mole of the diene to give XVI; if the two compounds are boiled together for a minute or less (74), 2 moles of the diene are added to give XVII. α-Naphthoquinone adds 1 mole of the diene in boiling ethanol, giving XVIII.



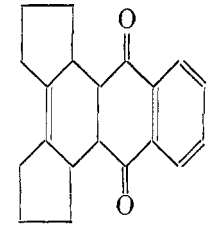
XV



XVI

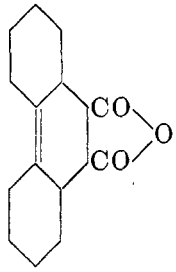


XVII

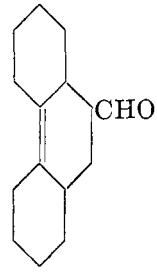


XVIII

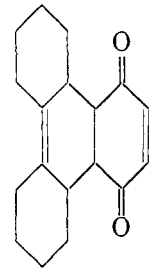
The corresponding compound with six-membered rings, bis-1-cyclohexenyl, adds maleic anhydride (5, 74, 232) to give the reduced 9,10-phenanthrenedicarboxylic anhydride (XIX). Acrolein gives the reduced 9-aldehydophenanthrene (XX). *p*-Benzoquinone yields the reduced 9,10-benz-1,4-phenanthrenequinone (XXI) (74) when the generators are dissolved in boiling ethanol. When the generators are boiled together without any solvent, the product is the reduced 1,2,3,4,5,6,7,8-tetrabenz-9,10-anthraquinone (XXII). α-Naphthoquinone gives the reduced 1,2,3,4-dibenzanthraquinone (XXIII).



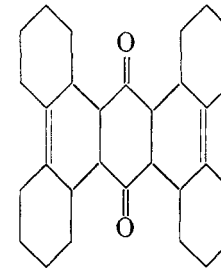
XIX



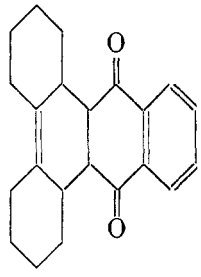
XX



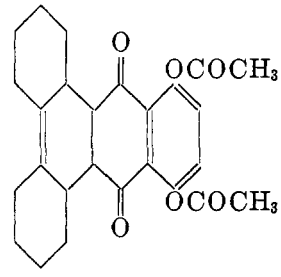
XXI



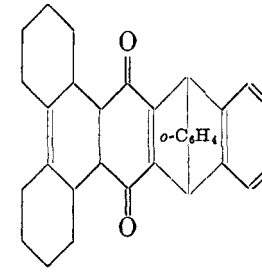
XXII



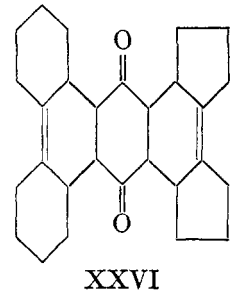
XXIII



XXIV



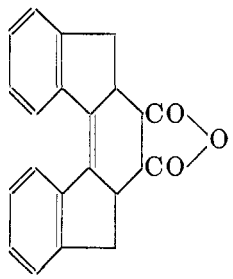
XXV



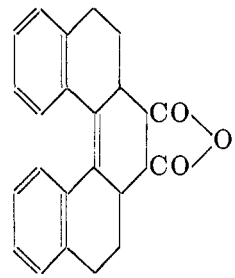
XXVI

Bis-1-cyclohexenyl is also added by naphthazarin diacetate (74) to give XXIV, and by 9,10-dihydro-9,10-endo-*o*-phenylene-1,4-anthraquinone (74) to give XXV. The quinone XVI, formed from bis-1-cyclopentenyl and *p*-benzoquinone in boiling methanol, will add a mole of bis-1-cyclohexenyl when the two are refluxed together (74), yielding XXVI.

Benzologs of the two above dienes have been studied. Bis-1-indenyl (340) has been shown to add maleic anhydride to give the reduced anhydride (XXVII), and 1,1′-bidialin (bis-3,4-dihydro-1-naphthyl) likewise gives the reduced anhydride (XXVIII). The bidialin addition does not take place as readily as does the bis-1-cyclohexenyl addition (297, 352). Barnett (74) reported failure to obtain a pure maleic anhydride addition product with bidialin, and stated that no reaction was observed between bidialin and *p*-benzoquinone or α-naphthoquinone.



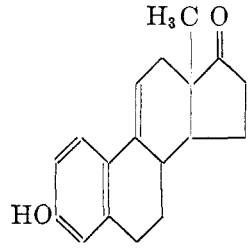
XXVII



XXVIII

Benzologs of 1-vinyl-1-cyclohexene have also been studied. 6-Methoxy-1-vinyl-3,4-dihydronaphthalene has been studied extensively, because the products formed are of importance in that they are preliminary products obtained in the rapidly developing field of sterol syntheses by diene reactions (93, 129, 130, 131, 132, 133). By choice of suitable dienophiles, adducts possessing the sterol-ring structure may be prepared, as shown in table 6.

The adduct of 2-methylcyclopenten-3,4-dione given in table 6 has been converted (132) into an isomer of estrone (XXIX).



XXIX

The semicyclic enynes, 3,4-dihydro-1-naphthylacetylene and its 6-methoxy derivative, add ethylenic and acetylenic dienophiles; the latter type of dienophile gives derivatives of 9,10-dihydrophenanthrene as adducts. Propiolic acid (130) gives a mixture of 9,10-dihydrophenanthrene-1- and 2-carboxylic acids on reac-

TABLE 6

Diene syntheses of 6-methoxy-1-vinyl-3,4-dihydronaphthalene

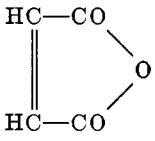
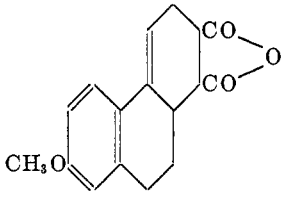
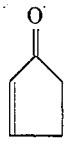
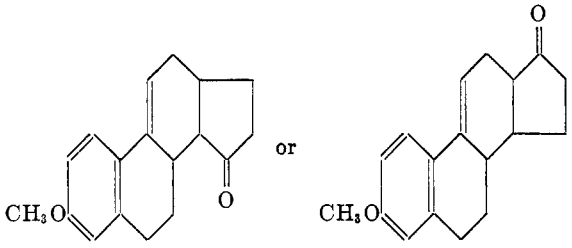
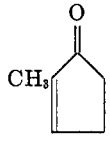
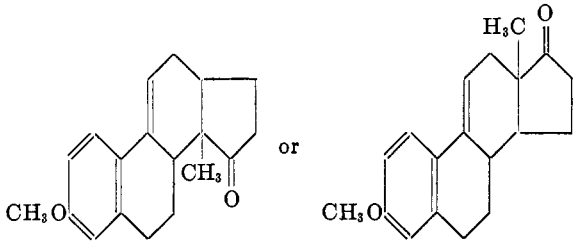
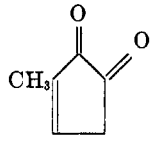
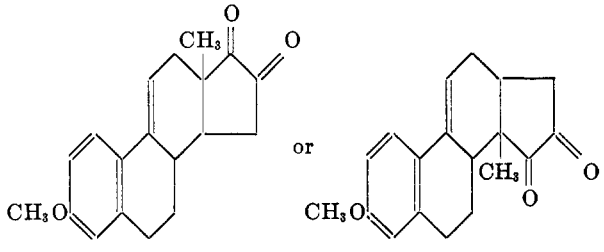
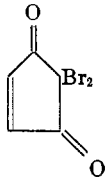
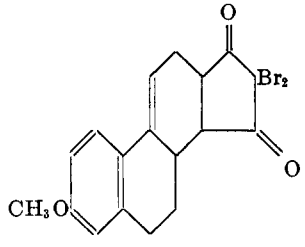
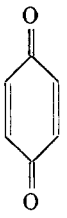
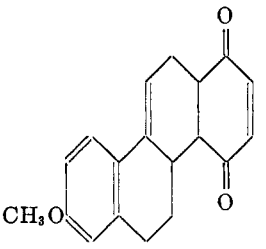
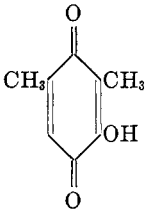
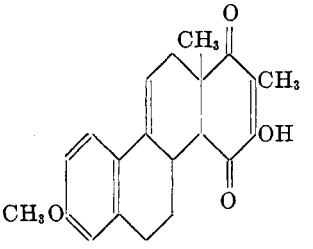
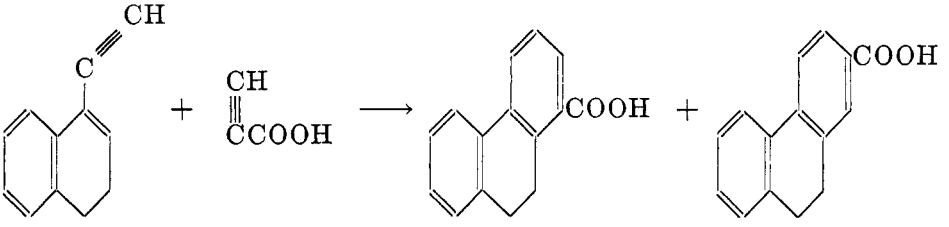
DIENOPHILE	PRODUCT
	
	
	
	
	

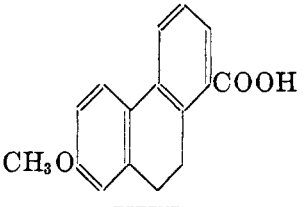
TABLE 6—*Concluded*

DIENOPHILE	PRODUCT
	
	

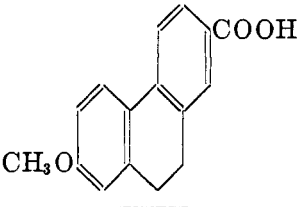
tion with 3,4-dihydro-1-naphthylacetylene, the 1-carboxylic acid being formed in greater amount.



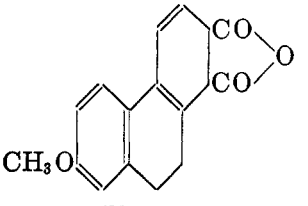
6-Methoxy-3,4-dihydro-1-naphthylacetylene adds propiolic acid (130) to give both XXX and XXXI. It does not add *p*-benzoquinone (130), but does add maleic anhydride (131), giving XXXII.



XXX



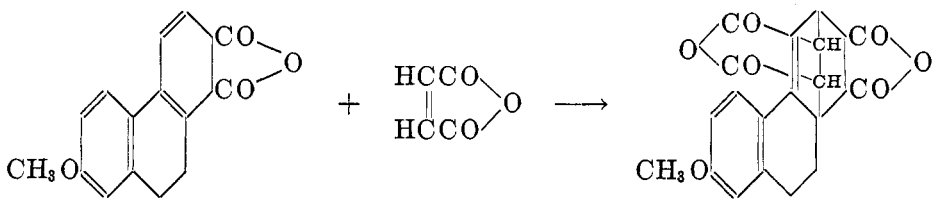
XXXI



XXXII

Since XXXII contains the 1,3-cyclohexadiene ring, it should be capable of adding further quantities of dienophiles. *p*-Benzoquinone does not add, but

interaction occurs (130) in which the quinone is reduced to hydroquinone and XXXII is converted into the anhydride of phenanthrene-1,2-dicarboxylic acid. The hydroquinone appears in the form of quinhydrone. On the other hand, maleic anhydride is added to give a bridged dianhydride (131):

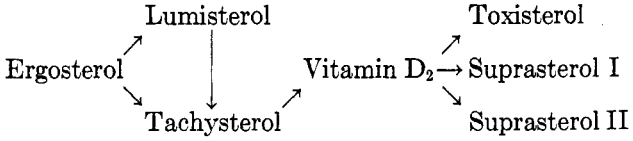


In this manner it may be seen that 3,4-dihydro-1-naphthylethylene and 3,4-dihydro-1-naphthylacetylene and their derivatives offer excellent possibilities as intermediates in the syntheses of the sterols and their derivatives. The reactions of the sterols themselves in the diene synthesis will be considered next.

VII. STEROLS

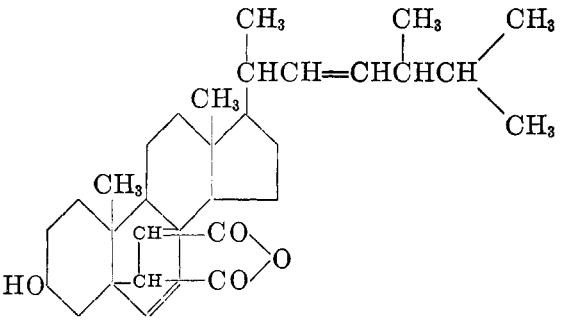
A. Ergosterol and derivatives

In the investigation of the various sterols and sterol derivatives from the standpoint of the diene synthesis, maleic and citraconic anhydrides have been almost the sole dienophiles employed. Certain of the irradiation products of ergosterol are active toward dienophiles. Lettré (282) indicates the successive formation of irradiation products as follows:



The use of acidic dienophiles in the investigations of the activities of the sterols in the diene synthesis is evident when one considers that the sterol adducts derived from such dienophiles are also acids. The adducts may therefore be separated from unchanged sterol simply by extracting with alkali, filtering from unchanged sterol, and precipitating with acid. Excess maleic or citraconic acid remains dissolved in the aqueous mother liquors.

Ergosterol adds maleic anhydride (282, 363, 366), best at a temperature of 135°C. Addition hardly occurs at room temperature and only slowly at 80°C. The same holds true for ergosteryl acetate (252, 366). The maleic anhydride adduct of ergosterol has structure I, and the corresponding adduct of ergosteryl acetate has a similar structure (253, 364). However, ordinary ergosteryl acetate shows only partial reaction with maleic anhydride (366), for a residue of dihydroergosteryl acetate remains unattacked. Distillation of the adduct of ergosteryl acetate and maleic anhydride in high vacuum gives maleic and succinic anhydrides, and a portion of the ergosteryl acetate may be recovered (366).



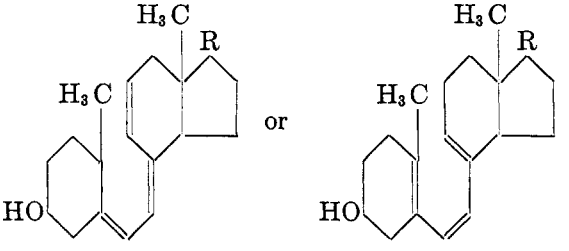
I

This recalls the formation of succinic anhydride and *p*-cymene by distillation of the adducts of maleic anhydride with α-phellandrene and with 1,3-menthadiene (page 388). Apparently a portion of the ergosteryl acetate appears as a dehydroergosteryl acetate, which probably possesses an aromatic ring. Reduction of the ergosteryl acetate–maleic anhydride adduct leads to initial hydrogenation of the double bond in the side chain. When ergosterol itself is reduced, the conjugated system is attacked first. By reduction of the ergosteryl acetate adduct and heating, 22-dihydroergosteryl acetate is produced, saponification of which gives 22-dihydroergosterol (364). 22-Dihydroergosterol, of course, adds maleic anhydride (362) to give a compound identical with I, except that the side chain is saturated. Windaus and Lüttringhaus (366) dispute this addition to a certain extent by saying that "dihydroergosterol" does not add maleic anhydride. There are three possible dihydroergosterols, only one of which has the conjugated-double-bond system required for the diene synthesis.

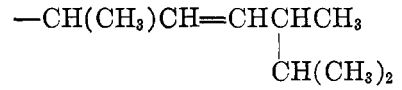
A tetrahydroergosteryl acetate (235) has been reported to add maleic anhydride. If this can be repeated, then the way is paved for an investigation of the mechanism of the reaction, for presumably the tetrahydroergosteryl acetate contains but one double bond.

Dehydroergosteryl acetate (235) adds maleic anhydride to give an adduct which appears to exhibit dimorphism. It may be distilled unchanged at 220°C. and in the cathode-glow vacuum (10^{-4} mm. of mercury), but decomposition into the generators occurs at 240°C. Dehydroergosterol itself also forms an adduct with maleic anhydride (234).

Tachysterol contains four double bonds and is formed from ergosterol on irradiation, when the central six-membered ring is opened. Lettré (282) suggests two alternative structures for the sterol, as shown below:



where R is



Lettré calls attention to the fact that, while ergosterol requires a temperature of 135°C. for the addition of maleic anhydride, tachysterol will add citraconic anhydride at room temperature (282). This adduct contains only two double bonds and its formation is interpreted as meaning that two molecules of citraconic anhydride have added, probably by addition of one molecule of citraconic anhydride followed by wandering of a double bond in the resulting product to give a conjugated system which then adds the second molecule of citraconic anhydride. It is difficult to understand how such a wandering could occur readily at room temperature, however.

The next product in the irradiation sequence is vitamin D_2 (calciferol). It and its acetate add maleic anhydride (296, 368). Calciferol, like tachysterol, possesses an isolated double bond and three conjugated double bonds. There have been no reports to the effect that calciferol adds two molecules of maleic anhydride, however.

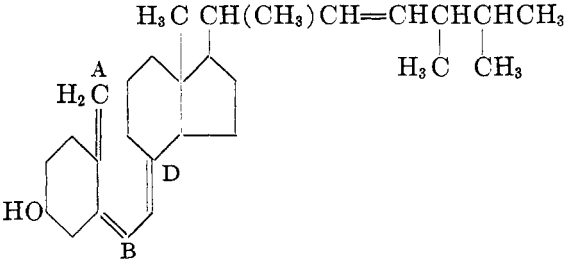
Heating calciferol to 190°C. results in ring closure and disappearance of a double bond with the formation of two isomeric products, isopyrovitamin and pyrocalciferol. Two double bonds are present in a single ring in each isomer, and each adds maleic anhydride (296).

Irradiated ergosterol was found to have lost its antirachitic power when treated with maleic anhydride or citraconic anhydride (367), thus indicating that vitamin D_1 contains conjugated double bonds. An earlier observation (361) indicated that maleic anhydride would not react with irradiated ergosterol, which led to the conclusion that the conjugated system of ergosterol is destroyed by irradiation. This is false, as was shown above.

The reaction of citraconic anhydride with irradiated ergosterol is incomplete, some 10 to 20 per cent remaining unattacked. The tachysterol which may be isolated from irradiated ergosterol reacts nearly as readily with citraconic anhydride (369) as it does with maleic anhydride.

Pure vitamin D_2 adds citraconic anhydride very slowly (365) and it is to be expected that the maleic anhydride addition proceeds more rapidly (368).

Windaus and Thiele (368) give the formula of calciferol as



and they state that maleic anhydride adds to carbon atoms A and B rather than to B and D. If the latter addition did occur, a ring with gem-substitution (a spirane) would be formed. This reaction would be expected to be much slower than the reaction between maleic anhydride and the combination of A and B.

Windaus and Lüttringhaus (366) divide the ergosterol derivatives into three classes according to their abilities to add dienophiles. Class I compounds react readily with maleic anhydride on staining at room temperature for several days, and include tachysterol, dehydroergosterol, one of the three isoergosterols, and certain irradiation products of ergosterol. Class II compounds, comprising ergosterol and its acetate, barely exhibit reaction at room temperature but react readily at 135°C. Class III compounds show no reaction, and comprise a dihydroergosterol, ergosterols D and F, the other two isoergosterols, and the products of the over-irradiation of ergosterol.

When ergosteryl acetate is treated with hydrogen chloride, the reaction products may be separated to some degree through the use of maleic anhydride (360). The adducts are separated by solution in caustic alkali and are decomposed into their generators by heating in high vacuum.

B. Cholesterol and derivatives

Cholesterol derivatives have been investigated only slightly with regard to their abilities to add dienophiles. 2,4-Cholestadiene adds maleic anhydride readily in boiling xylene solution (339). The mixture termed "cholesterilene," —the main constituent of which is probably 3,5-cholestadiene,—adds maleic anhydride to some extent, but the product appears to be abnormal (194, 338). 3,5-Cholestadiene itself possesses a *trans*-butadienoidal configuration, and it adds maleic anhydride only under drastic conditions (338, 347). The product obtained is probably polymeric, for its alkali salts are insoluble in water (distinction from other sterol–maleic anhydride adducts). 2,4-Cholestadiene is claimed to give an abnormal addition product with maleic anhydride (194), although it contains the 1,3-cyclohexadiene ring. This claim has been disputed (339).

Coprastadienol (365) adds maleic anhydride easily to give an adduct which is best isolated in the form of the acetate by treatment of the adduct with acetic anhydride, since the adduct acetate crystallizes far better than does the original adduct.

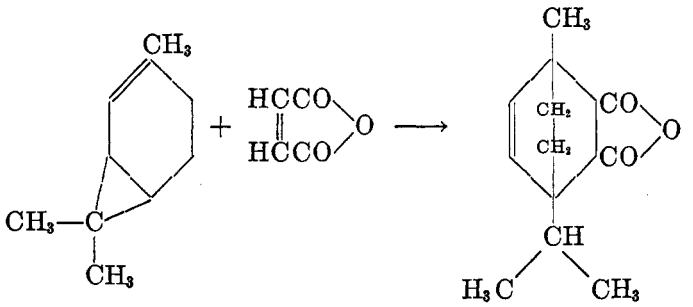
$\Delta^{6,8(14)}$-Cholestadiene and $\Delta^{7,9(11)}$-cholestadiene possess *trans*-butadienoidal configurations; they do not add maleic anhydride (405). On the other hand, $\Delta^{7,14}$-cholestadiene possesses a *cis*-butadienoidal configuration and is able to add maleic anhydride.

VIII. TERPENES AND TERPINOID BODIES IN THE DIENE SYNTHESIS

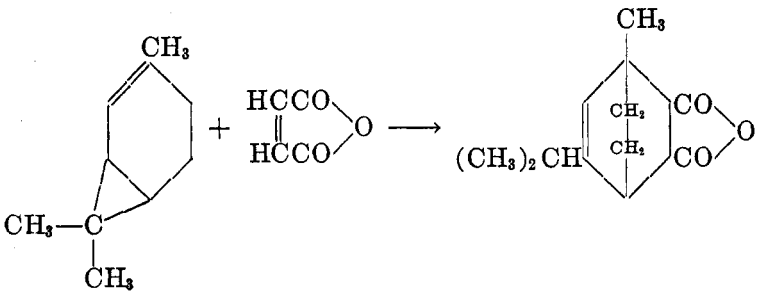
The terpenes often react as dienes, and sometimes even if they do not contain conjugated double bonds. It is likely that isomerization takes place prior to

the consummation of the diene reaction; a somewhat satisfactory explanation can be advanced on this basis for most of the reactions.

Hultzsch (238) obtained addition of maleic anhydride to α-pinene, limonene, terpinolene, and 3-carene at reflux temperatures. None of the adducts appeared to be identical. On the other hand, when maleic acid was employed as dienophile, all the adducts were identical, and were the same as the adduct obtained from 1,3-*p*-menthadiene and maleic acid. Diels (162) observed that 3-carene[2] formed an adduct with maleic anhydride, which did not appear to be identical with the adduct from 1,3-*p*-menthadiene and maleic anhydride. He took the view that, inasmuch as the cyclopropane ring often acts as a double bond (as in the addition of hydrogen bromide or bromine to cyclopropane; see, however, Kharasch, Fineman, and Mayo (266)), the cyclopropane ring could function as a double bond and be in conjugation with the double bond of what he called 3-carene[2].



Diels apparently neglected to consider the equally likely mechanism:



A somewhat more satisfactoy rexplanation for certain of these observations may possibly be found in the application of generally known facts of terpene

[2] There is controversy in the literature regarding the carenes. Goodway and West (228) state that 3-carene does not contain a cyclopropane ring in conjugation with the double bond, while Hultzsch (238) states that Diels used 4-carene in his reaction. Hultzsch obtained addition with both 3-carene and 4-carene.

TABLE 7

The additions of maleic anhydride to dienic acids and their derivatives

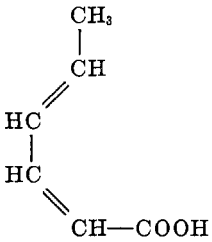
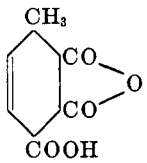
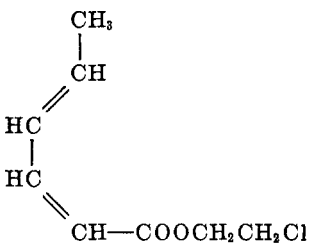
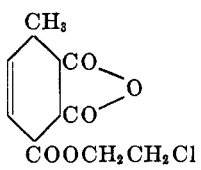
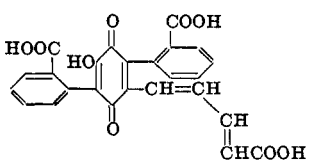
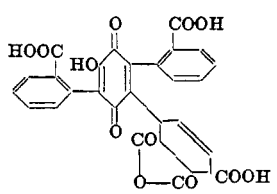
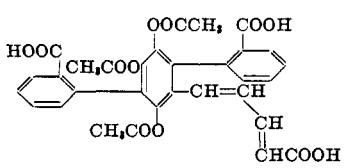
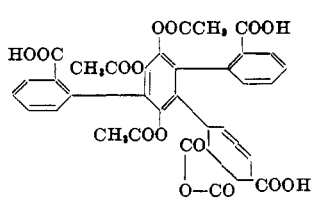
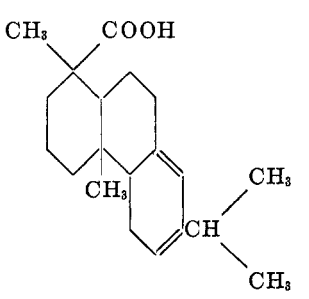
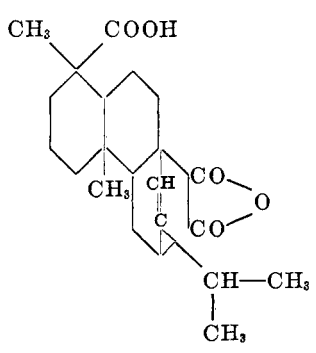
DIENE	DIENE STRUCTURE	PRODUCT STRUCTURE	REFERENCE
Sorbic acid.....			(199)
β-Chloroethyl sorbate			(347)
Muscarufin			(269)
Triacetylleuco-muscarufin			(269)
l-Pimaric acid ...			(69, 205, 317, 324, 359)

TABLE 7—*Continued*

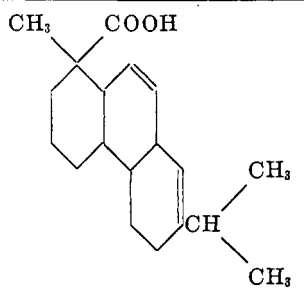
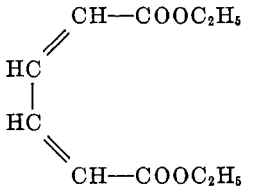
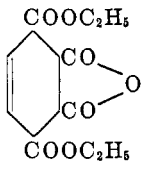
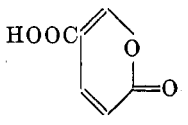
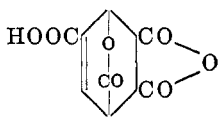
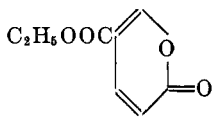
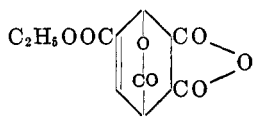
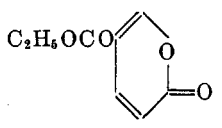
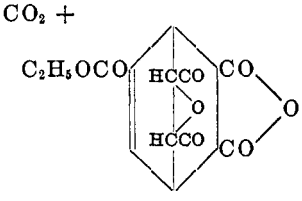
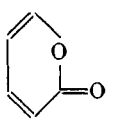
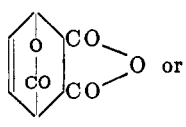
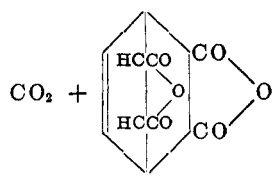
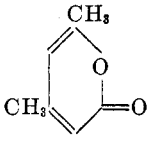
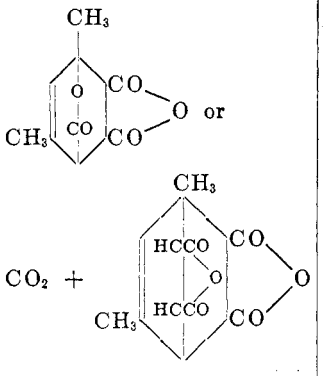
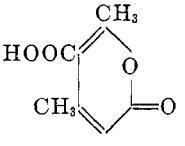
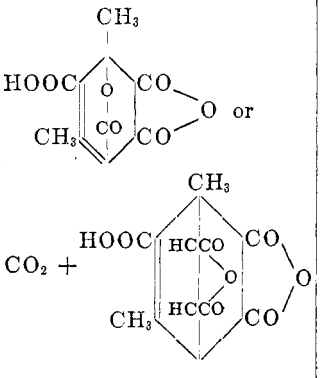
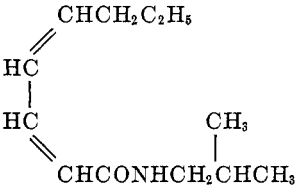
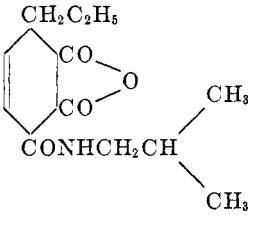
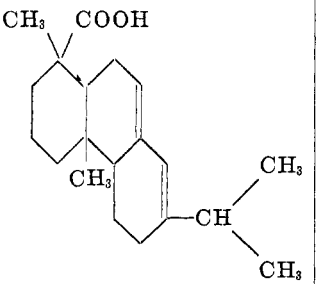
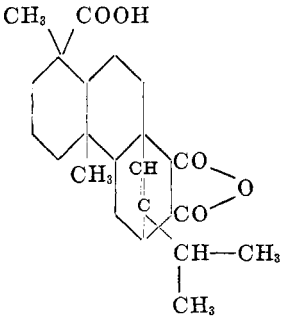
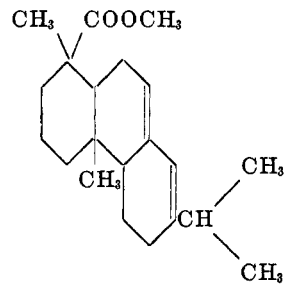
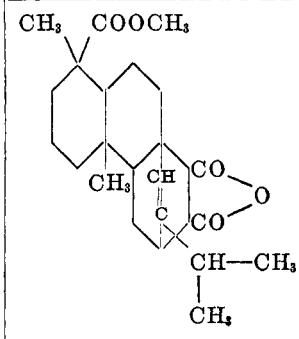
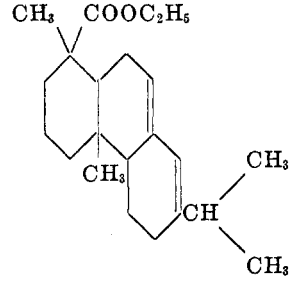
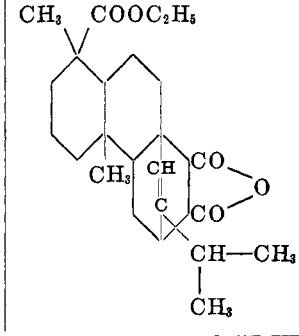
DIENE	DIENE STRUCTURE	PRODUCT STRUCTURE	REFERENCE
d-Pimaric acid...		Polymeric product	(314)
Ethyl *trans*-*trans*-muconate.			(199)
Cumalinic acid ..			(145)
Cumalinic ester (at 110°C.)			(145)
Cumalinic ester (at 138–140°C.).		CO_2 + 	(145)
Cumalin.....		 or CO_2 + 	(145)

TABLE 7—*Continued*

DIENE	DIENE STRUCTURE	PRODUCT STRUCTURE	REFERENCE
Dimethylcumalin.....			(145)
Isodehydracetic acid.....			(145)
Spilanthole.....			(64)
Abietic acid*			(55, 314)

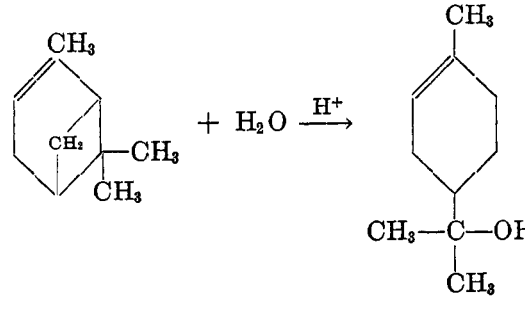
* Fieser's structure for abietic acid. Its adduct is identical with that obtained from *l*-pimaric acid.

TABLE 7—*Concluded*

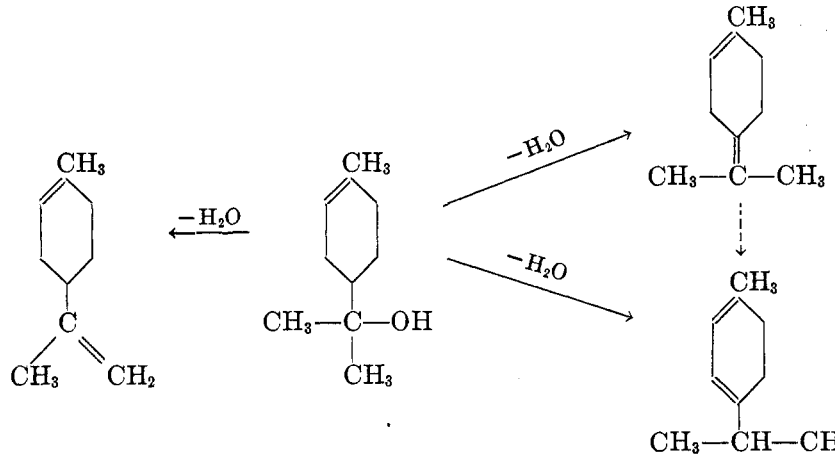
DIENE	DIENE STRUCTURE	PRODUCT STRUCTURE	REFERENCE
Methyl abietate			(314)
Ethyl abietate			(314)

chemistry. The explanations here advanced fail when applied to the maleic anhydride additions, though they explain the maleic acid additions.

In the case of the pinene addition, it is known that α-pinene is transformed into terpineol when boiled with dilute acids, and also into α-terpinene and terpinolene simply by refluxing with clay (312):

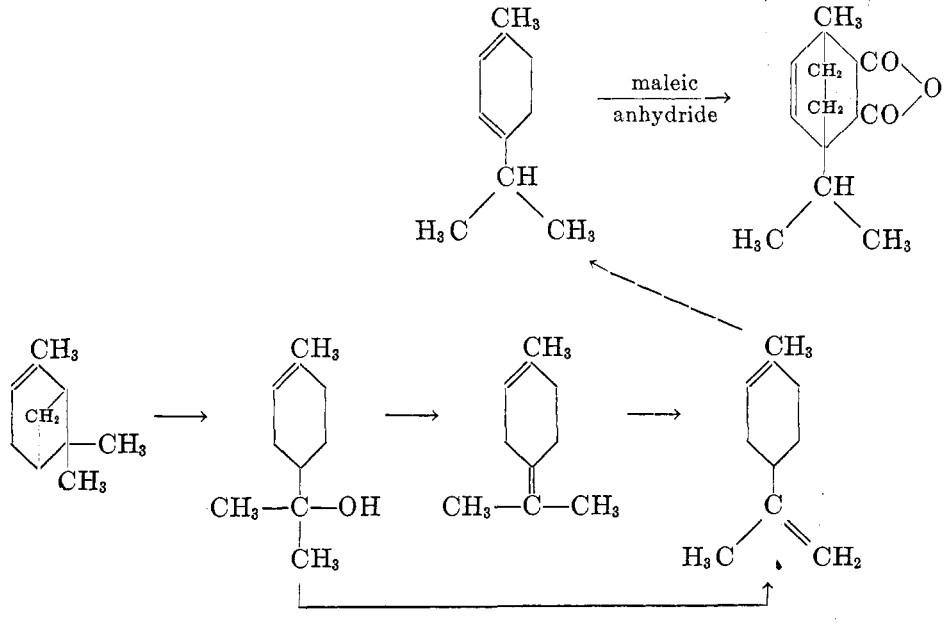


The tertiary alcohol can lose water and form *dl*-limonene or terpinolene. Alder and Rickert (15) obtained mostly 1,3-menthadiene by direct degradation:



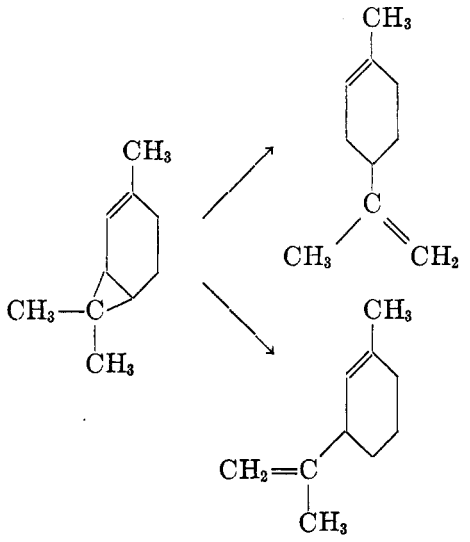
Semicyclic double bonds such as exist in terpinolene wander into the ring under the influence of acids. In this manner terpinolene gives terpinene (1,3-*p*-menthadiene) very readily with dilute acid. Dilute acids also transform terpineol into terpinolene, *dl*-limonene, or 1,3-*p*-menthadiene, depending on the conditions. Alcoholic sulfuric acid will convert limonene into 1,3-*p*-menthadiene.

Heat alone will convert α-pinene into 1,3-*p*-menthadiene, accounting for the observation of Hultzsch (237) that high-temperature turpentine reacts more thoroughly with maleic anhydride than does low-temperature turpentine. Since an acid medium (due to maleic anhydride or maleic acid) exists in the α-pinene diene synthesis, the following sequence of reactions is likely:

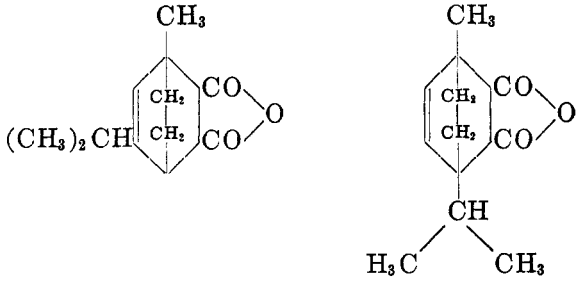


Since limonene and terpinolene are intermediates in the transformation of α-pinene to 1,3-*p*-menthadiene, their reactions with maleic acid are obvious. Support for this mechanism is furnished by the observation (226) that terpinolene and γ-terpinene do not add maleic anhydride at room temperature.

3-Carene (4-carene) is easily isomerized by dilute acids to a mixture of *dl*-limonene and sylvestrene:



It may be that sylvestrene is convertible into 1-methyl-3-isopropyl-1,3-cyclohexadiene by acids, though it is one of the most stable of the terpenes. According to this view the 3(or 4)-carene adduct with maleic anhydride is a mixture of I and II:



I II

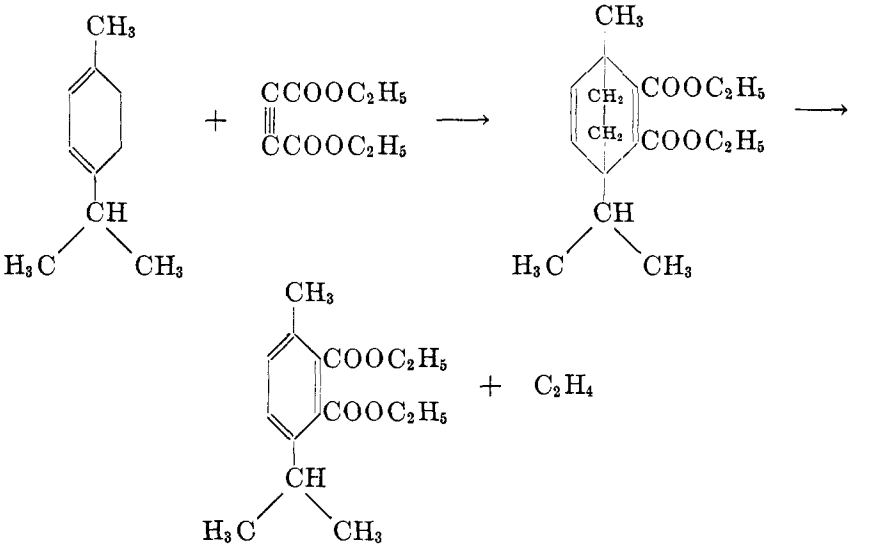
This view does not take cognizance of the report that the maleic acid adduct of 3(or 4)-carene is identical with the adducts of the other three terpenes. It would be indicated that at the hydrogen-ion concentration furnished by maleic acid, conversion of 3-carene or 4-carene to sylvestrene is at a minimum and that nearly all conversion is to *dl*-limonene. Since maleic anhydride would

scarcely be expected to be more acidic than maleic acid, it would follow that sylvestrene formation does not occur with maleic anhydride.

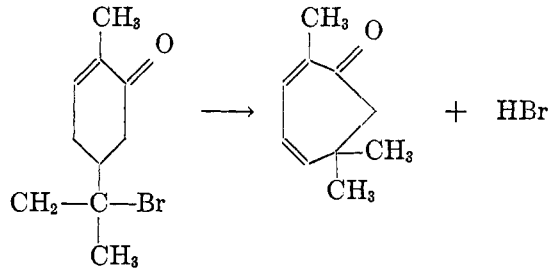
Arbuzov (56, 57; see also 388) passed α-pinene over copper chromite. At 300°C., a mixture of 80 per cent α-pinene and 20 per cent alloöcimene was obtained, while at 375°C. the composition was 23 per cent α-pinene, 31 per cent alloöcimene, and 12 per cent *dl*-limonene, whilst at 400–410°C., the composition was 20 per cent α-pinene, 23 per cent *dl*-limonene, 20 per cent alloöcimene, and 36 per cent of an unidentified terpene. Contrary to Arbuzov (388), β-pinene similarly yields alloöcimene.

Slobodin (332) has isomerized limonene and vinyl-3-cyclohexene by passage over floridin at 210–240°C. Limonene isomerized easily but vinylcyclohexene was more resistant. The isomerization products of each reacted vigorously with maleic anhydride. It was postulated that vinylcyclohexene isomerized to ethylidene-2-cyclohexene, but the presence or absence of other aromatics was not demonstrated or stated. No proof was given for the structures of the isomerizates.

Diels and Alder and their students (8, 15, 162) and Tischchenko and Bogomolov (342; see also 230) showed that α-terpinene added maleic anhydride. Diels and Alder (8, 15, 162), by reaction with acetylenedicarboxylic ester and then deolefinization of the adduct, proved that α-terpinene was 1,3-*p*-menthadiene.



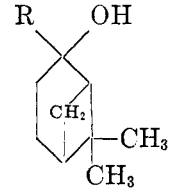
A second terpene was produced in addition to α-terpinene when terpineol was dehydrated (15). This contained conjugated double bonds, for it added acetylenedicarboxylic ester easily. This adduct did not decompose on distillation; hence the terpene is not a cyclohexadiene derivative. Alder and Rickert (15) feel that the material is a cycloheptadiene, and for circumstantial evidence they indicate von Baeyer's (70) carvone hydrobromide reaction:



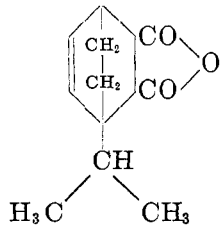
The cycloheptadienone is eucarvone. In accordance with this reaction, they believe their terpene to be eucarvene. Prior to this study, it had been generally believed that "terpinene" derived from terpineol was a mixture of 1,3- and 1,4-*p*-menthadienes.

Acrolein has been reported (342) to "add" to *dl*-limonene to give "a liquid which gives *dl*-limonene on distillation at atmospheric pressure."

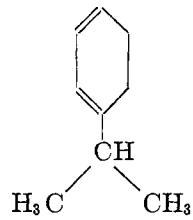
A few more instances are available of diene reactions of terpinoid bodies which do not contain conjugated double bonds (284). These terpinoid bodies are interesting in that they contain no unsaturated linkages whatever, yet give diene reactions. These are the so-called nopinols,



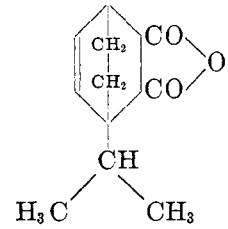
in which R may be hydrogen or alkyl. When R is hydrogen, the adduct I is obtained with maleic anhydride. This is the same as obtained from apo-α-terpinene (II). There is also obtained a material which is probably nopinyl maleate or fumarate, and a residue of probably the same composition. When R is methyl, the exclusive product of the reaction is III, which was obtained from α-pinene, terpinolene, 3(4?)-carene, α-terpinene, and *dl*-limonene with



I



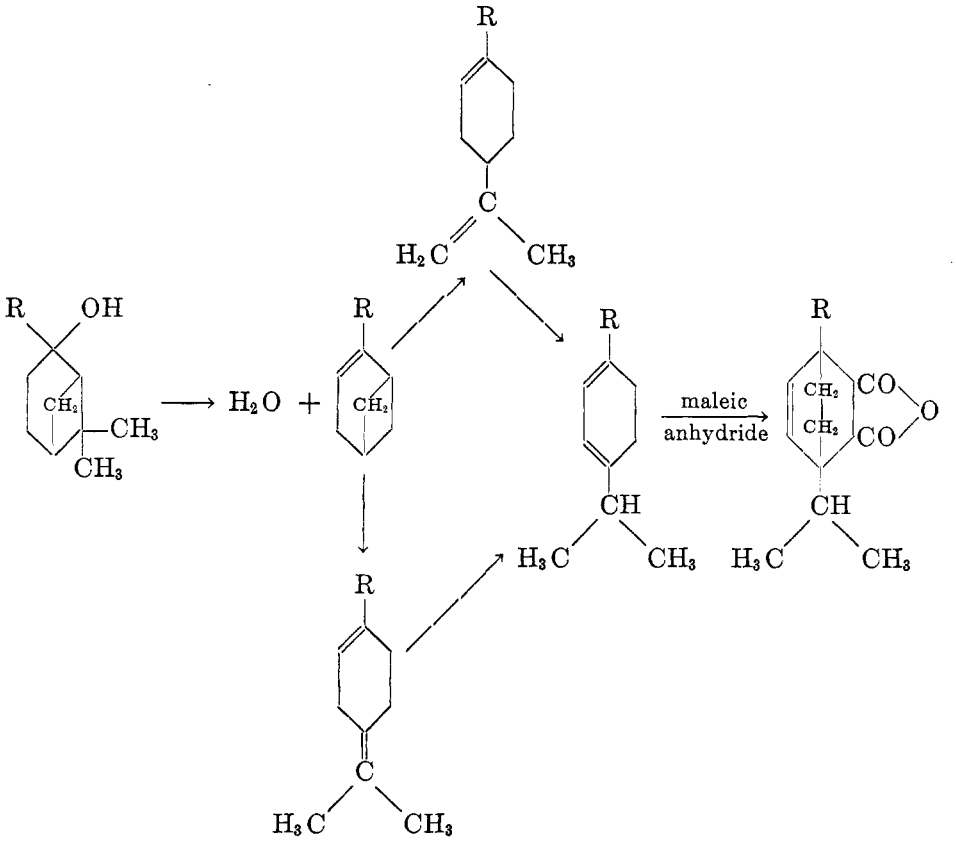
II



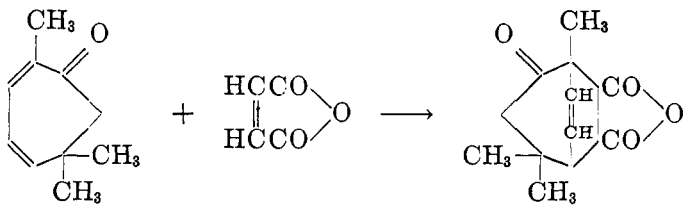
III

maleic acid. Similar products are obtained when R is phenyl or benzyl. The difficulty in obtaining a clean-cut reaction with nopinol may be attributed to the fact that when R is hydrogen, the material is a secondary alcohol, but when

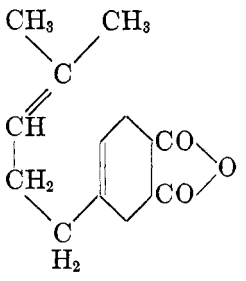
R is an alkyl or aryl group, the material is a tertiary alcohol. Evidently one of the first steps in the process of addition is the elimination of water to form norpinene, pinene, or a related compound dependent on the identity of R. It will be recalled that secondary alcohols are dehydrated less readily than are tertiary alcohols; hence the difficulty when R is hydrogen. The sequence of reactions appears to be



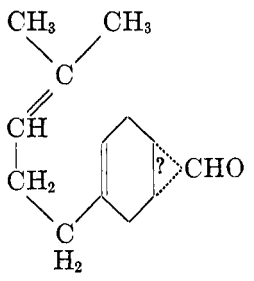
von Baeyer's eucarvone (70) has been observed to add maleic anhydride (33, 353) and acetylenedicarboxylic ester (15) (see page 404).



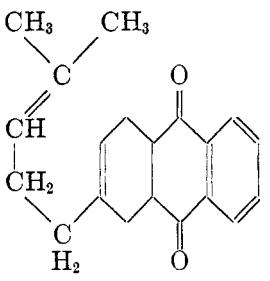
Myrcene has been found to add maleic anhydride (144, 313, 407), acrolein (139), and α-naphthoquinone (224) giving IV, V, and VI, respectively.



IV



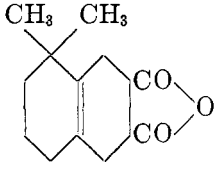
V



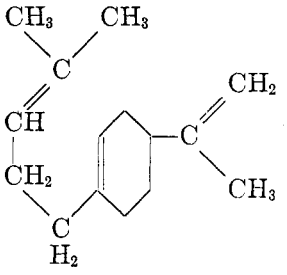
VI

Bromine water (144) or formic acid (313) will cyclize the maleic anhydride adduct to an octalin derivative (VII). This cyclizate yields 2,3,8-trimethylnaphthalene on dehydrogenation (313).

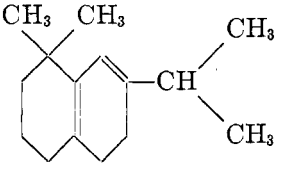
Isoprene will add to myrcene (315, 329) to give the so-called cycloisoprene-myrcene (VIII). Semmler and Jonas (329) observed this reaction as early as



VII



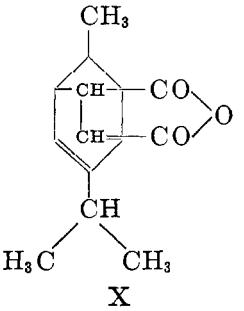
VIII



IX

1913 and found that *dl*-limonene is also produced (by dimerization of the isoprene). VIII cyclizes with formic acid (315) to give IX, the double-bond wandering being quite likely because of the acid conditions of the cyclization reaction. Dehydrogenation of the cyclizate gives eudalene.

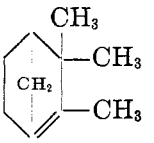
Menogene (2,4(8)-*p*-menthadiene) is an example of a terpene containing a conjugated semicyclic double bond in the *trans*-butadienoid configuration. This adds maleic anhydride (236) to give an adduct, presumably X; but the conditions of the reaction, together with the fact that addition actually occurred, may well lead one to wonder if the semicyclic double bond had not wandered into the ring before addition actually occurred. At least a portion of the product may be the maleic anhydride adduct of 1,3-menthadiene or of 2,4(5)-menthadiene.



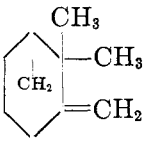
X

At least one quinone has been reacted with terpenes other than α-phellandrene (see the section on homocyclic dienes for α- and β-phellandrenes), and this is the reaction of naphthazarin with alloöcimene (59). The hydrocarbon has also been caused to react with maleic and citraconic anhydrides (56, 57, 238, 407). It is of interest to note that the melting points of the adducts of alloöcimene with maleic and with citraconic anhydrides are almost identical (56, 57).

As might have been expected, neither camphene nor camphor reacts with maleic anhydride (238). If the semicyclic double bond of camphene were to wander into the ring (this is unlikely, inasmuch as compounds of the type represented by XI are unknown in terpene chemistry and are unstable with respect to compounds of the type represented by XII), it is still a matter of some difficulty to understand just how rupture of the endomethylene bridge could possibly occur so as to give another double bond required for a conjugated system.

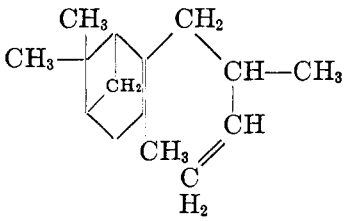


XI

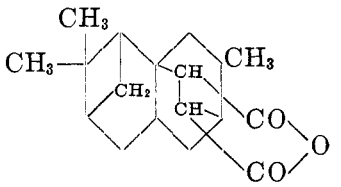


XII

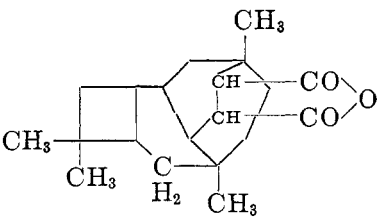
Ruzicka and Zimmermann (318) observed that the mixture of sesquiterpenes known as caryophyllene reacts with maleic anhydride to give a 70 per cent yield of adduct. At the time (1935) the formula of the main constituent of caryophyllene was given as XIII. In order to account for the formation of an adduct which appeared to be saturated (unattacked by ozone, alkaline permanganate, perbenzoic acid, or tetranitromethane), they assumed addition of maleic anhydride to the isolated system of double bonds, followed by cyclization, giving the compound XIV. If true, this would be a singular example of an anomalous diene reaction. A revised formula (XV) given in 1936 (reference



XIII

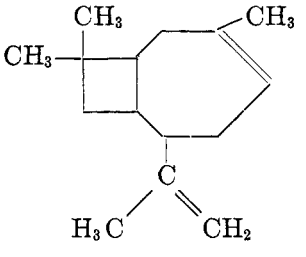


XIV

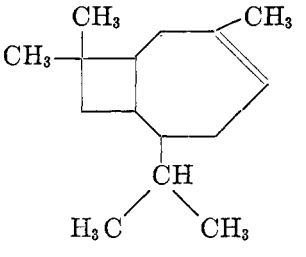


XV

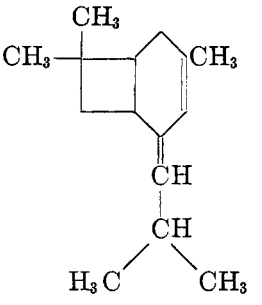
319) appeared to state the case no more satisfactorily. In 1938, Rydon (320) proposed that the main constituent of caryophyllene is a cycloheptene derivative (XVI), and that the maleic anhydride adduct is formed from a conjugated isomer (XVII). Since an alternative isomer (XVIII) is a *trans*-butadienoidal compound, it should hardly be expected to add maleic anhydride. Goodway and West (229) made a number of comments on the problem, among which was that absorption-spectrum studies of caryophyllene indicate the absence of any appreciable quantity of conjugated dienes. They also stated that if Rydon is correct, then the double bond of the adduct is highly unreactive, as it is in many terpinoid substances, since the apparently saturated nature of the adduct has been demonstrated. They finally concluded that the adduct is not formed by the diene synthesis.



XVI



XVII



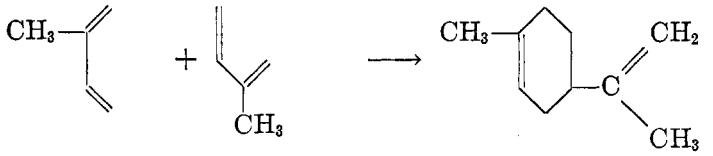
XVIII

IX. DIMERIZATION

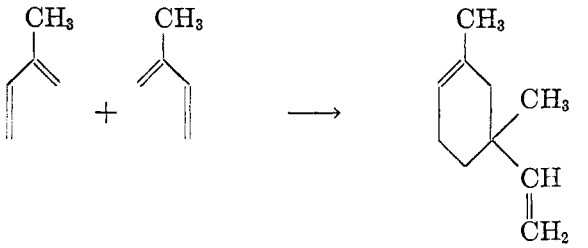
A number of dimerization reactions of the type which may be represented by the diene synthesis had been discovered half a century or more ago. Representative of those observed around the beginning of the twentieth century is that of Wallach (349) who, in the year 1895, synthesized *dl*-limonene by dimerization of isoprene in the absence of oxygen and peroxides and employed elevated temperatures. Diels and Alder (136) considered this as a type of diene synthesis and extended the reaction to other dienic hydrocarbons. In many instances there were obtained trimers, tetramers, and pentamers. It was found that an elevated temperature is generally necessary to bring about dimerization, and an antioxidant such as hydroquinone or catechol is beneficial in elimination of the catalytic effects of peroxides on polymerization reactions which lead to the formation of polymers of high molecular weights.

Diels and Alder (136) postulated that the formation of *dl*-limonene occurred according to reaction A. Lebedev (275) thought that the geminal compound 1-vinyl-1,3-dimethyl-3-cyclohexene (reaction B) was formed at room temperature; but later Wagner-Jauregg (345) found that while isoprene forms *dl*-limonene at high temperatures, the product formed at room temperature was diprene (reaction C):

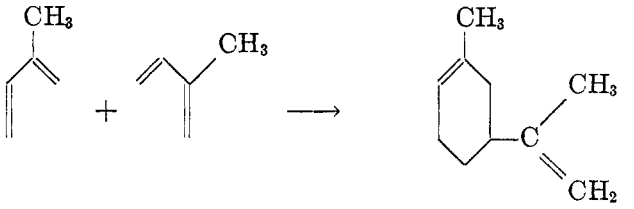
(A)



(B)

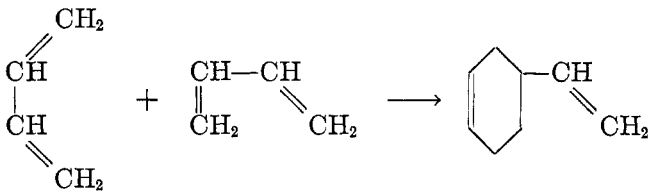


(C)

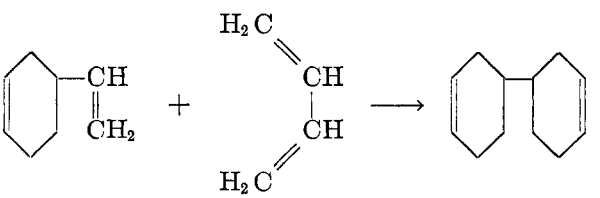


Absence of products resulting from reaction B is in harmony with the general observations concerning optional additions of dienophiles. These are explained in greater detail on page 329.

In extension of the diene synthesis to the dimerizations of other hydrocarbons, it was found that butadiene gave vinyl-3-cyclohexene (16, 276, 334) when heated at 180°C. with hydroquinone:

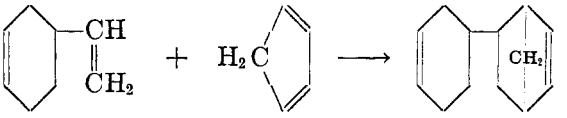


The product (vinylcyclohexene-3 or 4-vinylcyclohexene) does not add dienophiles, and therefore any proposed structure containing a conjugated system is unlikely. Dehydrogenation gives ethylbenzene; styrene may also be formed. Vinylcyclohexene-3 can add butadiene at elevated temperatures under antioxidant conditions to give butadiene trimer, which is 1,2,3,6,1′,2′,5′,6′-octahydrobiphenyl:



The fact that the trimer gives diphenyl on dehydrogenation establishes its ring structure and also affords strong evidence for the presence of a double bond on the side chain of the dimer. This evidence couples with the fact that the dimer does not react with dienophiles to show that the structure of vinylcyclohexene fits the facts best.

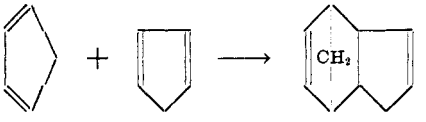
Vinylcyclohexene-3 will add other dienes as well as butadiene. Cyclopentadiene is added to give 1,2,3,6,1′,2′,5′,6′-octahydro-3,6-endomethylenebiphenyl:



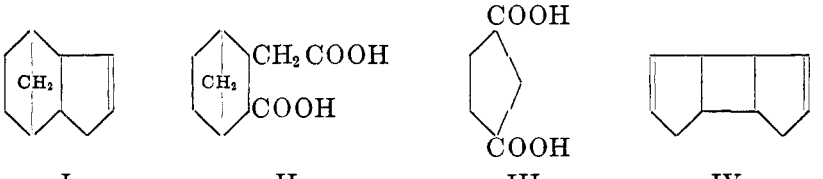
A considerable amount of α-tricyclopentadiene was formed in the above diene synthesis. The term "α-tricyclopentadiene" is a misnomer; it and similar names should be construed as meaning the trimer of cyclopentadiene.

1,2,3,4-Tetramethylbutadiene (311) has been observed to dimerize to the corresponding octamethyl-4-vinylcyclohexene.

Pirsch (302) discusses the various possible structures of the dimer of cyclopentadiene. This dimer is often referred to as dicyclopentadiene, especially in the older literature. Alder and Stein published a series of papers dealing with the proof of structure of this and other polymers, making a number of observations which led to deduction of their structures. Apparently the dimerization of cyclopentadiene is a true diene synthesis (135), proceeding as follows:

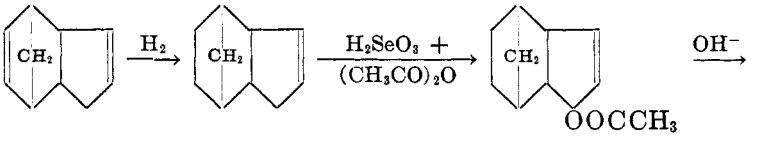


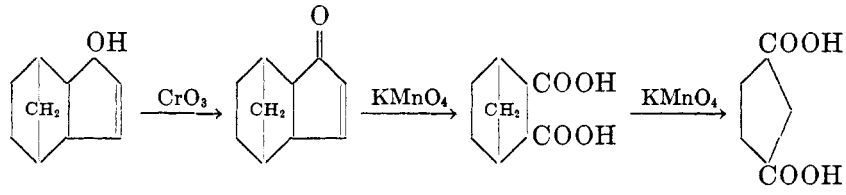
The degradation of the dimer to cyclopentane-1,3-dicarboxylic acid was accomplished in the following sequence of reactions: Partial hydrogenation of the dimer gives I, oxidation of which gives 3,6-endomethylenehexahydrohomophthalic acid (II). Further oxidation of II gives cyclopentanedicarboxylic acid (III). Such a degradation renders structure IV for the dimer inadmissible.



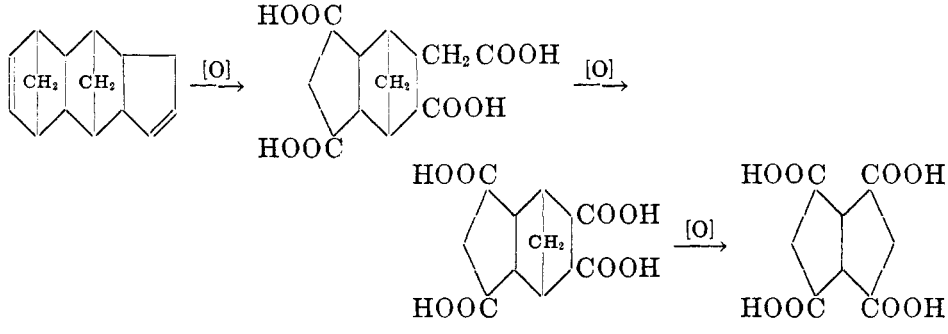
I II III IV

The dimer may be degraded to cyclopentane-1,3-dicarboxylic acid by another route (34):



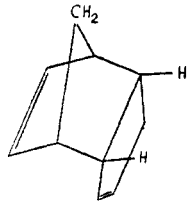


The reaction of phenyl azide with the double bond of the bicycloheptene ring appears to be rather specific, and was much used by Alder and Stein as a test for the presence of this ring in cyclopentadiene polymers. The test is not limited to detecting this ring in the polymers of cyclopentadiene, for the adducts of maleic anhydride and other dienophiles with cyclopentadiene give this test as well as does cyclopentadiene dimer or trimer (31). The evidence is strong for the presence of the bicycloheptene (3,6-endomethylenecyclohexene) ring in the dimer. The trimer also contains the bicycloheptene ring, as indicated by the phenyl azide reaction, and also by degradation of the trimer (31, 36) to a 3:3:0-bicyclooctanetetracarboxylic acid by methods analogous to those used in the degradation of the dimer:

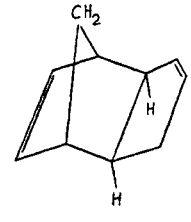


The double bond of the bicycloheptene ring is much more reactive than the other double bond of the dimer. Selective hydrogenation of this bond is accomplished with ease, and nitrosyl chloride adds to this bond rather than to the other. It would seem logical, therefore, that when the dimer adds another mole of cyclopentadiene to form the trimer, the reactive double bond is involved. This is indeed the case.

The dimer exists in two stereoisomeric forms, owing to the presence of the endomethylene group (29). The endo-isomer has the methylene group and the five-membered ring on opposite sides of the cyclohexene ring, whereas the exo-isomer has these on the same side. These are illustrated in the three-dimensional sketches below:



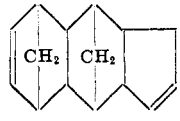
endo

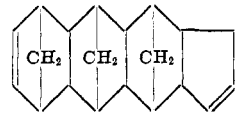


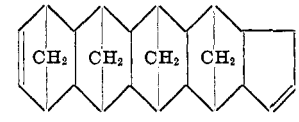
exo

Addition takes place between two molecules of cyclopentadiene to give the endo-form, according to the general rules of stereochemical addition of dienes discussed in a later section (see page 497).

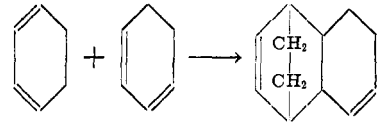
Since the trimer, tetramer, pentamer, etc., of cyclopentadiene are all formed by a series of diene syntheses involving the active double bond of the bicycloheptene ring as the "carbonylenic" double bond (though no carbonyl group is present, this term is used to denote the dienophilic double bond), the structures of these compounds are V, VI, and VII, respectively, in which all the endomethylene groups lie on one side of the six-membered ring system and the unsaturated terminal five-membered ring lies on the other side of that ring system.


V

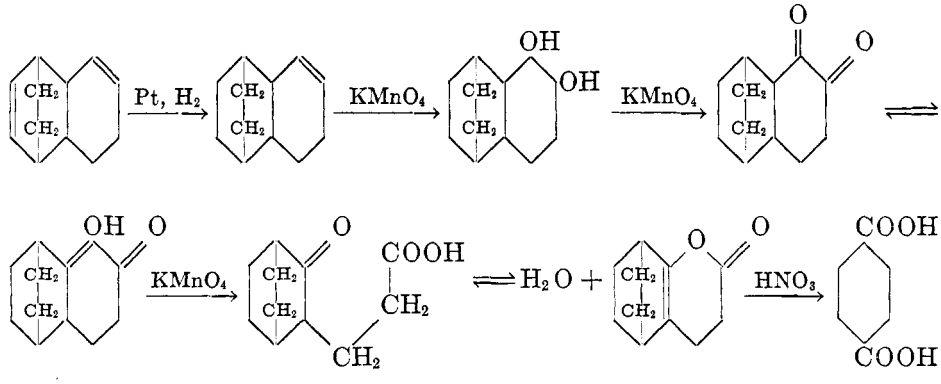

VI


VII

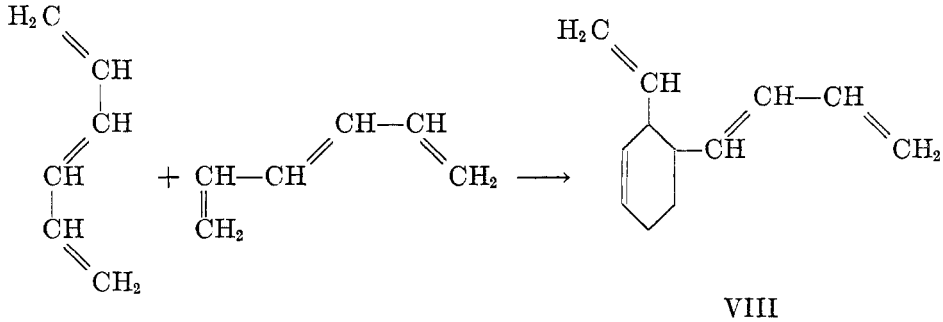
Cyclohexadiene dimerizes in a manner similar to that of cyclopentadiene (22, 46). When considered as a diene synthesis, the product would be of the structure indicated by the reaction



The structure of the product was elucidated (22) by a series of reactions as indicated in the scheme below, giving *cis*-hexahydroterephthalic acid as final product:

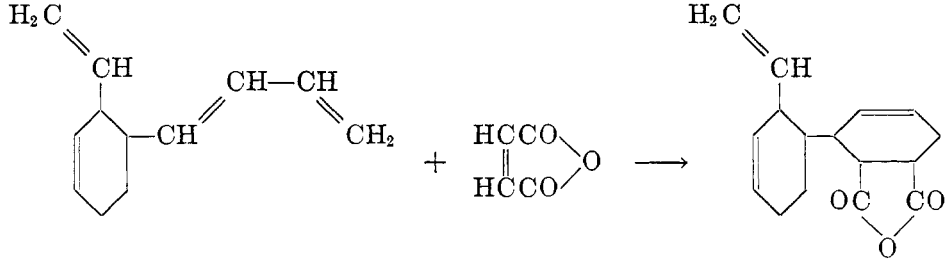


Kharasch and Sternfeld (268) prepared 1,3,5-hexatriene by the reaction of allyl chloride with a solution of sodium amide in liquid ammonia. This was found to dimerize to give VIII, the structure of which was proved.

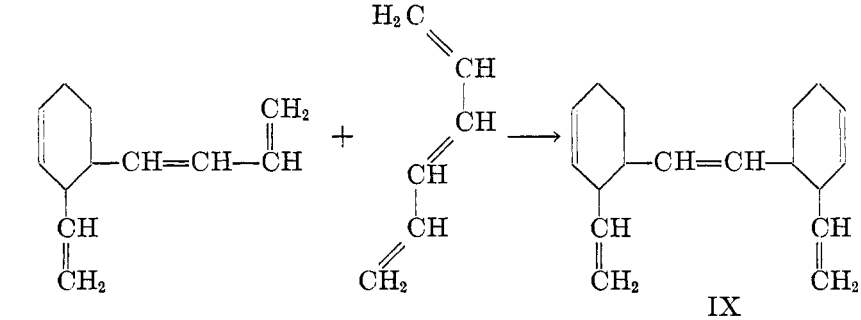


VIII

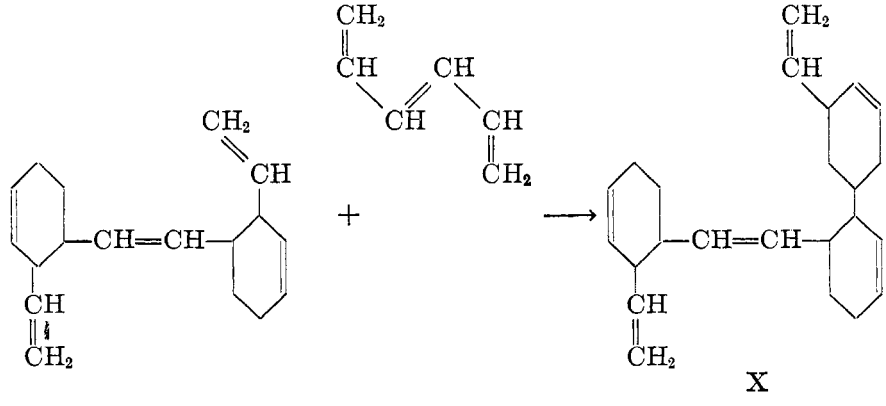
Since the dimer possesses a pair of conjugated double bonds, it adds maleic anhydride:



Hexatriene was also found to form a trimer and a tetramer, IX and X, respectively, the structures of which were postulated but not proved:

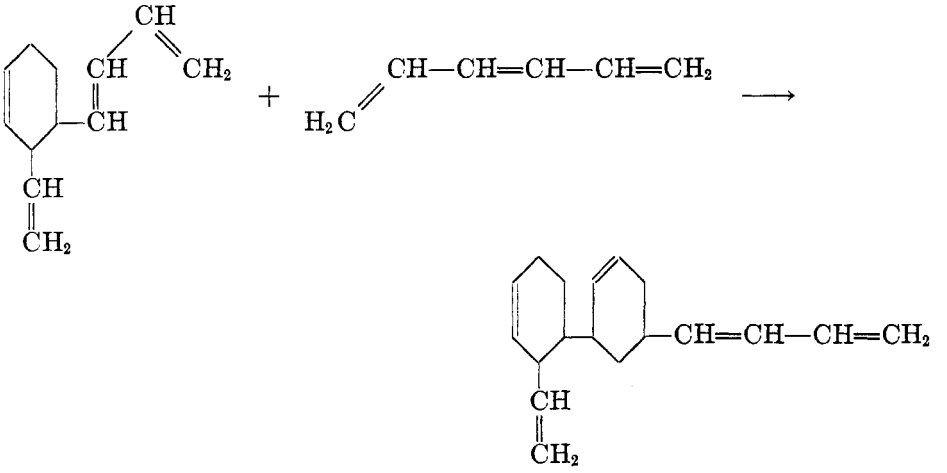


IX

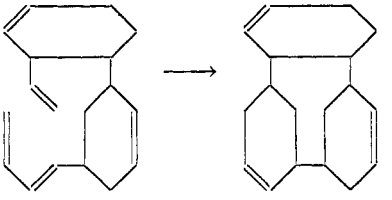


X

It should be evident that there are several means whereby trimerization and tetramerization may occur. It is quite possible for trimerization to occur according to the scheme:

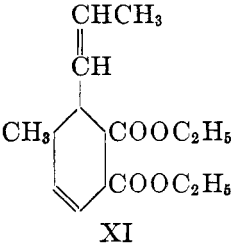


This trimer might undergo self-stabilization through an intramolecular diene reaction:



It may be seen, therefore, that in the absence of structural proof, the structures of hexatriene trimer and tetramer as postulated by Kharasch and Sternfeld are open to question.

According to Farmer (197), sorbic ester dimerizes at 230°C. to give three isomeric dimerides, which are cyclohexene derivatives. A trimeride is also formed, but this is so insoluble in the monomer–dimer mixture that no appreciable amounts of tetramer are formed. Kuhn and Deutsch (272) state that only one dimer is formed and that its structure is that of XI.

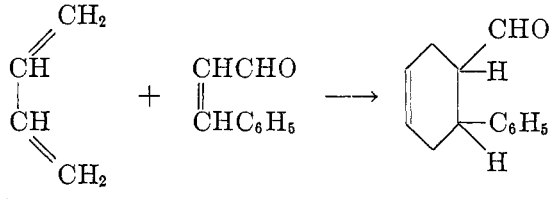


XI

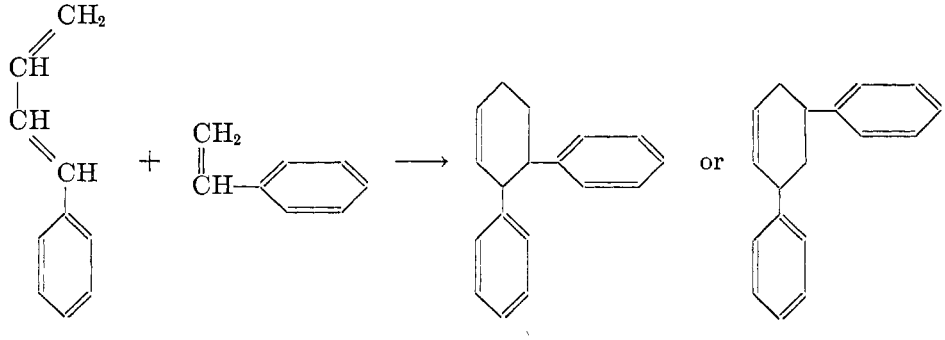
1-Phenylbutadiene (82) appears to dimerize abnormally, since the dimer is not a cyclohexene derivative but is 1-(β-styryl)-2-benzyl-3-cyclopentene. This structure was proved by oxidation of the compound to benzoic and α-benzyltricarballylic acids. Farmer (197) states that, with the exception of 1-phenylbutadiene, the dimers of conjugated dienes and trienes are cyclohexenic compounds.

Allied to the dimerization reactions are those reactions in which hydrocarbons act as the dienophiles, though these hydrocarbons may not be dienes or result from the dimerization reaction type of diene synthesis. Styrene is such a hydrocarbon, as is its relative, indene. Certain other hydrocarbons have been discussed in connection with the reactions of certain dienes, such as the cyclones, myrcene, alloöcimene, etc. Hydrogenated diphenyls may be synthesized from styrene, while indene gives rise to fluorene derivatives. Thus, butadiene and styrene give 1,2,3,6-tetrahydrobiphenyl; 2,3-dimethylbutadiene and styrene give 1,2,3,6-tetrahydro-4,5-dimethylbiphenyl; butadiene and indene give 1,1a,4,4a-tetrahydrofluorene; 2,3-dimethylbutadiene and indene give 1,1a-4,4a-tetrahydro-2,3-dimethylfluorene (17). Cyclopentadiene and indene give 1,1a,4,4a-tetrahydro-1,4-endomethylenefluorene, while cyclopentadiene and styrene give 1,2,3,6-tetrahydro-3,6-endomethylenebiphenyl (17). Inasmuch as these additions are carried out at elevated temperatures and the adduct of cyclopentadiene and styrene contains the bicycloheptene ring, there is also found a quantity of a secondary product formed by the addition of cyclopentadiene to the active double bond of the cyclopentadiene–styrene adduct.

An isomer of the product obtained from styrene and butadiene may be obtained by decarboxylation of the adducts of 1-phenylbutadiene and acrylic or maleic acid (17). By choice of suitably substituted phenylbutadienes, butadienes, or styrenes, almost any desired hydrogenated diphenyl may be prepared. If styrene is substituted in the side chain with an aldehyde group (cinnamaldehyde), the reaction with butadiene occurs at ordinary temperatures (17):



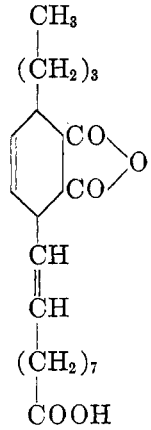
1-Phenylbutadiene and styrene should yield terphenyl derivatives:



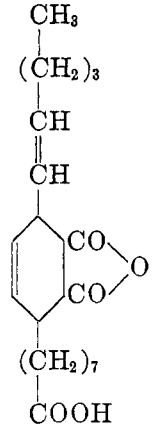
X. DIENIC ACIDS AND DERIVATIVES

Dienic acids the double bonds of which are conjugated may act as dienes in the diene synthesis. Esters of these acids can also react, as well as lactones and lactams of hydroxy- and amino-dienic acids. A fine example of the reaction of an enol as a dienic lactone is shown by γ-methylpyrone in its addition of dienophiles.

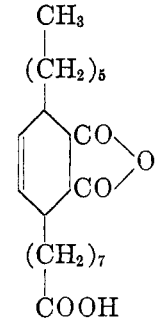
The glycerides of β-eleostearic acid and licanic acid have been shown to add maleic anhydride (258, 259). The reaction of β-eleostearic acid itself (θ,κ,μ-octadecatrienoic acid) has been reported (257) to give a product to which structure I has been assigned, although no evidence appears to have been advanced to disprove the alternative structure (II). Methyl β-eleostearate and α-eleostearic acid (295) have been shown to add maleic anhydride, and 9,11-licanic acid gives III with maleic anhydride (94).



I



II



III

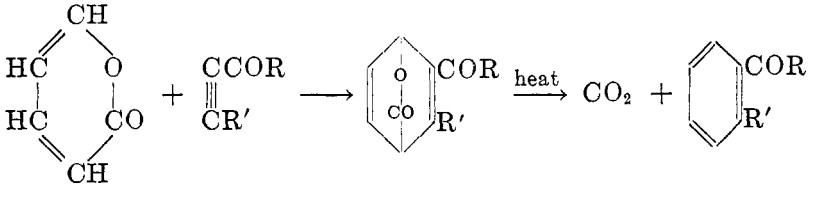
Sorbic acid forms one or more dimers (197, 272), as indicated on page 436. Kuhn and Deutsch state that only one dimer is formed (XI, page 435), basing this claim on the products obtained on decarboxylation of the dimer. Decarboxylation results in a cyclohexene which apparently undergoes isomerization to an *o*-propyltetrahydrotoluene. As is well known, cyclohexadiene is thermodynamically unstable, and *o*-propyltetrahydrotoluene appears to undergo dismutation under the pyrolytic conditions of the decarboxylation, so that the final products isolated are *o*-propyltoluene and *o*-propylmethylcyclohexane. A similar effect (272) is noted in the decarboxylations of the dimers of vinylacrylic acid and of β-styrylacrylic acid. Thus, vinylacrylic acid dimer gives trimeric hydrocarbons, ethylbenzene, and ethylcyclohexane. β-Styrylacrylic acid dimer gives biphenyls which are hydrogenated to varying extents and also biphenyl itself.

Sorbic acid esters add dienophiles. Ethyl sorbate adds benzoylethylene (47) to give 1,2,5,6-tetrahydro-3-methylbenzophenone-6-carboxylic ester, the struc-

ture of which was proved. β-Chloroethyl sorbate adds acryloyl chloride (347) to give 1,2,3,4-tetrahydro-4-methylisophthaloyl dichloride, the ester group being changed into the —COCl group through the action of excess acryloyl chloride. β-Chloroethyl acrylate is the by-product.

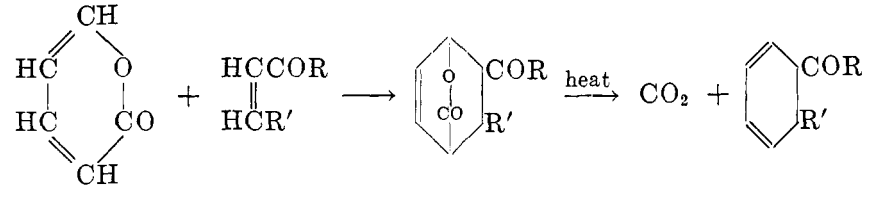
The addition of dienophiles to the dienic lactones which contain a six-membered lactone ring engenders products containing a lactone bridge. These split out carbon dioxide on heating, and this action occurs occasionally under the conditions of the reaction. The general statement of the action will depend upon whether an acetylenic or an olefinic dienophile is employed in the reaction. Schematically, the two routes are as shown below:

(A) With an acetylenic dienophile:

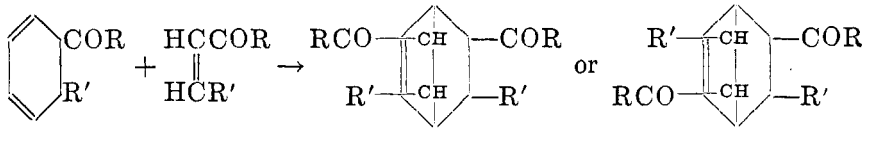


(B) With an olefinic dienophile:

(1)



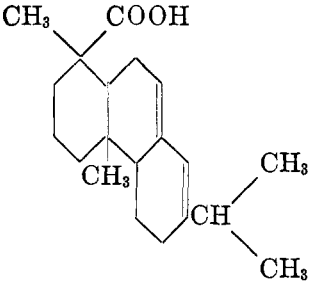
(2)



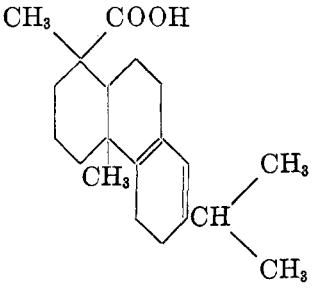
If the low-temperature adduct of cumalinic ester with maleic anhydride is esterified with methanol, carbon dioxide is eliminated. The product is not a trimellitic acid derivative but a trimesic ester. Apparently atmospheric oxidation occurs during the esterification reaction (145), for oxidation of the same adduct with bromine gives trimesic acid directly.

The structures of *l*-pimaric acid and of abietic acid are open to question only as far as the double-bond arrangement is concerned. Various structures have been proposed for these two acids, for their maleic anhydride adducts are identical, and one acid may be transformed into the other through the agency of heat. *l*-Pimaric acid adds maleic anhydride readily, even at room temperature (69, 205, 316, 317, 324, 359), while temperatures of not less than 100°C. are necessary to effect addition to abietic acid. Absorption-spectra studies indicate that the double bonds of *l*-pimaric acid are located in a single ring of the molecule (205), a fact which is consistent with the ease of addition of maleic

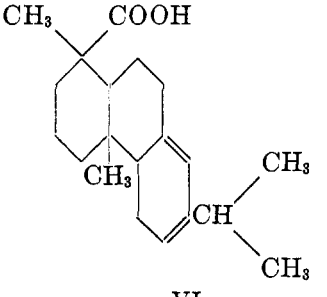
anhydride. The higher temperature is evidently necessary with abietic acid so that rearrangement to *l*-pimaric acid may occur. Fieser (205) feels that such interconversion is best expressed by assignment of structure IV to abietic acid. By a simple shift of a double bond (wandering of a semicyclic double bond), abietic acid could be converted into *l*-pimaric acid, to which Fieser assigns structure V:



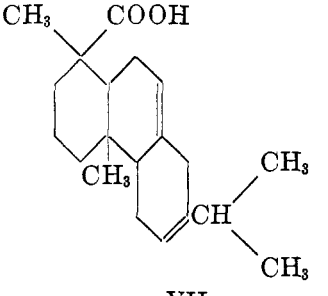
IV



V



VI



VII

If *l*-pimaric acid has structure V, then its adduct with acetylenedicarboxylic ester should evolve ethylene on strong heating (*cf.* the section on cyclohexadiene). Sandermann (324) found that such was not the case. No olefinic gases were evolved on heating the adduct, even to charring temperatures. For this reason Sandermann prefers structure VI for *l*-pimaric acid, and has worked out a mechanism for the isomerization of abietic acid of structure IV to *l*-pimaric acid of structure VI.

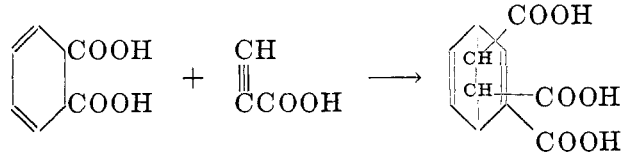
It should be pointed out that, if the Fieser formulas are followed, then addition of maleic anhydride to abietic acid should be similar to the addition of maleic anhydride to β-phellandrene. β-Phellandrene (228) gives a resinous product on refluxing with maleic anhydride. When distilled *in vacuo*, this resin affords a yield of 8 per cent of the adduct of α-phellandrene and maleic anhydride. Certainly the yields of adduct from abietic acid and maleic anhydride are far higher than this, for resinous polyesters of glycerol with the abietic acid–maleic anhydride adduct are in commercial use today (304). The author feels that, in lieu of other evidence, the assumption of the existence of a conjugated

system in abietic acid is not necessary, and that it may be represented by formula VII. This is analogous to the formula of terpinolene, which is easily converted into α-terpinene (1,3-*p*-menthadiene) by a variety of agents. A semicyclic double bond such as is given in formula VII tends to wander into the more unsaturated ring, and if abietic acid be formulated as VII, it would seem reasonable to expect wandering of the semicyclic double bond to give *l*-pimaric acid, as represented by formula VI. Repeated crystallization of abietic acid from methanol will bring about the change into *l*-pimaric acid, as will also heat.

d-Pimaric acid differs from *l*-pimaric acid in not adding maleic anhydride (359), *p*-benzoquinone, or α-naphthoquinone. These are added readily by *l*-pimaric acid at room temperature, and by abietic acid at higher temperatures (359). *p*-Xyloquinone is not added by any of these acids.

XI. AROMATIC POLYNUCLEAR HYDROCARBONS AND CERTAIN DERIVATIVES AS DIENES

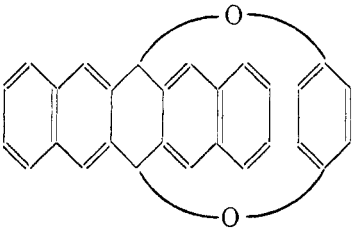
Benzene, the simplest of the aromatic hydrocarbons, does not react with maleic anhydride or with indene (291). An adduct, hypothetically obtainable from benzoic acid and maleic anhydride, probably could be obtained by addition of propiolic acid to 1,2-dihydro-*o*-phthalic acid:



In like manner, biphenyl (61) is inert toward *p*-benzoquinone, and naphthalene (291) is inert toward indene and *p*-benzoquinone. As a general rule, those polynuclear aromatic hydrocarbons which add dienophiles are those for which complete Kekulé structures for all benzene rings cannot be drawn. Such hydrocarbons are anthracene, naphthacene, 1,2-benzanthracene, etc. Hydrocarbons for which complete Kekulé structures can be drawn, such as benzene, naphthalene, and phenanthrene, almost invariably do not add dienophiles. Chrysene appears to be an exception to this rule, and 9,10-anthraquinone may be another exception.

Oddy (299), in 1923, observed a reaction between anthracene, maleic anhydride, and aluminum chloride and thought the product to be 9-anthroylacrylic acid. Research by the I. G. Farbenindustrie Aktiengesellschaft led to the issuance, in 1927, of a patent (239) covering the additions of α- and β-chloropropionic acids (which form acrylic acid *in situ*), acrylic, maleic, cinnamic, and crotonic acids, their esters, halides, and anhydrides to anthracene, 1,2-benzanthracene, chrysene, and their alkyl, alkoxyl, hydroxyl, and halogen derivatives to yield carboxylic acids or their derivatives suitable for use as dye or pharmaceutical intermediates. This patent appears to have been overlooked by Clar and by

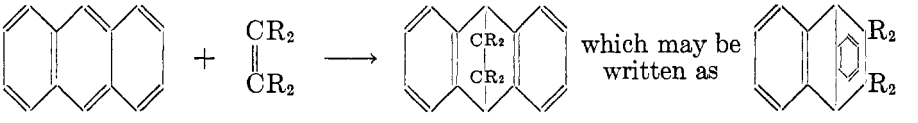
Diels and Alder, for as late as 1930 Clar and John (119) were of the opinion that the reaction product of *p*-benzoquinone and pentacene was of structure I:



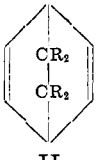
I

In 1931 Clar arrived at the true structure of the adduct (107) and investigated the reaction of anthracene with *p*-benzoquinone. Diels and Alder (138) immediately classified these reactions as diene syntheses and investigated the reactions of anthracene with other dienophiles. With maleic anhydride there was obtained an adduct of the same melting point as Oddy's compound.

The general statement of the anthracene–dienophile reaction is



Reversal of this reaction is to be anticipated, since the adducts possess the same type of ring structure as do adducts of 1,3-cyclohexadiene and acetylenic dienophiles (II).



II

It will be recalled that the $—CR_2—CR_2—$ bridge splits out when the adducts of cyclohexadienes with acetylenic dienophiles are heated, to yield an olefin, $CR_2{=}CR_2$. These adducts may, in a sense, be regarded as the adducts of the benzene derivative and the olefin, although such generators do not react in the diene synthesis to any measurable extent.

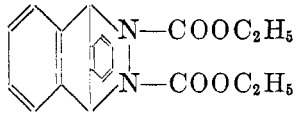
The extent of the reversal of the anthracene–dienophile reaction is dependent on the dienophile used; this is also true of other polynuclear hydrocarbons. In the case of anthracene adducts it has been shown that reversal is also dependent on substituents in the diene and their location on the three rings. Electronegative substituents and alkyl radicals have little or no effect when attached to positions in the terminal rings, but such substituents on the meso-positions may seriously decrease the tendency for adduct formation. This tendency reaches a maximum when the 9-substituent is the hydroxyl group, for adducts of the enol-form of anthrone appear incapable of existence (72). While anthrone will react with maleic anhydride, the reaction is not a diene synthesis (72). Hydrolysis of certain 9-substituted anthracene adducts of maleic anhydride,

such as those derived from 9-chloro- or 9-acetoxy-anthracene, would ordinarily be expected to lead to an adduct of the enol-form of anthrone with maleic anhydride. Instead, maleic anhydride (or acid) and anthrone are formed (72).

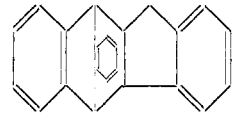
When the 9,10-substituents are alkyl groups, little effect is produced with regard to the end result of the synthesis. Usually the reaction rate is increased and the equilibrium point is nearly that of the parent hydrocarbon. Thus, 9,10-dimethylanthracene reacts much more rapidly than anthracene. 9,10-Diethylanthracene reacts more slowly, but still is more reactive than the parent hydrocarbon (391). 9,10-Diarylanthracenes react more slowly and incompletely than anthracene itself.

Linear fusion of benzene rings to the anthracene molecule favors addition of dienophiles, whereas angular fusion of the same rings tends to hinder such addition. Cook (125) took advantage of this phenomenon to separate 1,2-benznaphthacene from the 1,2,5,6- and 1,2,7,8-dibenzanthracenes, for the more nearly linear compound reacts much more readily with maleic anhydride than do the angular dibenzanthracenes.

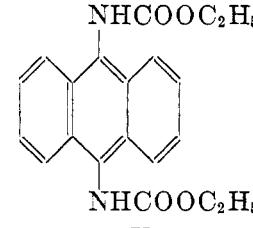
As a typical diene, anthracene adds even such dienophiles as azodicarboxylic ester (170), giving III, and indene (291) to give IV:



III



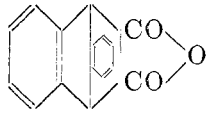
IV



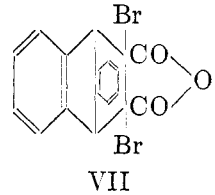
V

Oxidation of adduct IV gives 9,10-anthraquinone, thus indicating the points of addition. Heat decomposes adduct III into its generators, and the N—N bond of III is catalytically broken by hydrogen ion to give what is thought to be 9,10-bis(carboxyamino)anthracene diethyl ester (V).

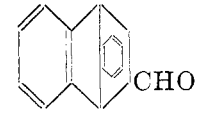
The maleic anhydride adduct of anthracene, VI, is also oxidizable to anthraquinone, as are the anthracene adducts of dibromomaleic anhydride, citraconic anhydride, and crotonic acid (149) and also the anthracene adduct of acrylic acid (73). The adduct of dibromomaleic anhydride (VII) may be debrominated by platinum and hydrogen to give the adduct obtainable directly from anthracene and acetylenedicarboxylic acid. Acrolein adds to anthracene (335) to give VIII, but incorporation of sulfurous acid into the reaction mixture stabilizes the acrolein to such an extent that a temperature of 130°C. is required for addition to take place.



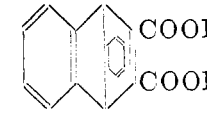
VI



VII



VIII



IX

TABLE 8

Addition of acetylenedicarboxylic ester to dienic acids and their derivatives

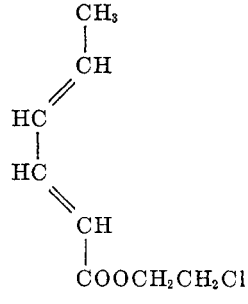
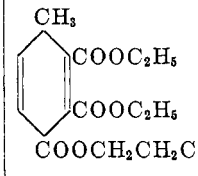
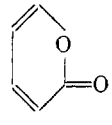
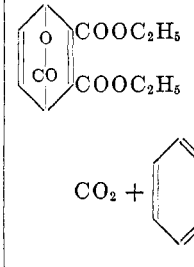
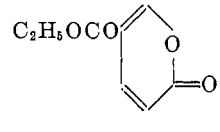
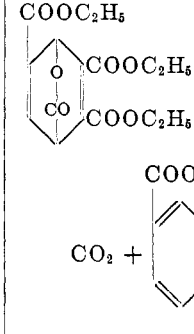
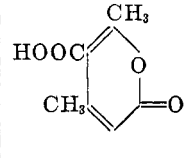
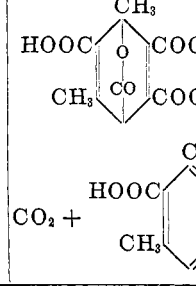
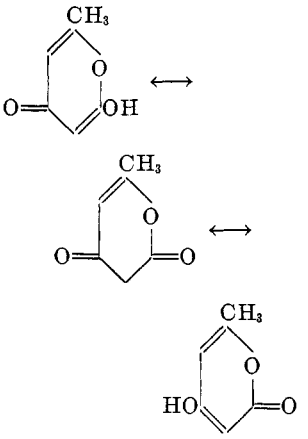
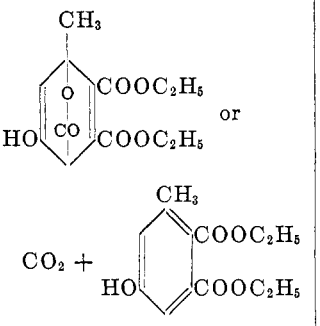
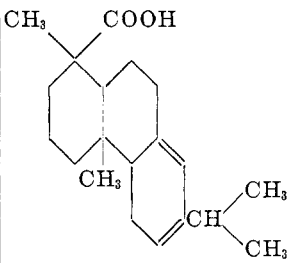
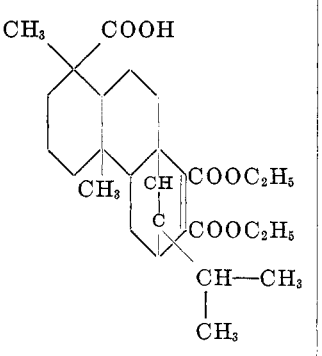
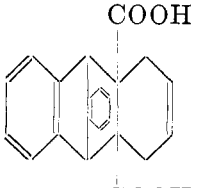
DIENE	DIENE STRUCTURE	PRODUCT STRUCTURE	REFERENCE
β-Chloroethyl sorbate.....			(347)
Cumalin.....			(14)
Cumalinic ester.....			(14)
Isodehydracetic acid.....			(14)

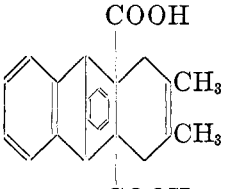
TABLE 8—*Concluded*

DIENE	DIENE STRUCTURE	PRODUCT STRUCTURE	REFERENCE
Enol-form of γ-methylpyrone ..			(14)
l-Pimaric acid			(324)

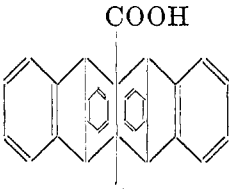
Acetylenedicarboxylic acid adds to anthracene to give an adduct (IX) which is rather reactive as a dienophile (149, 158). This adduct dienophile adds butadiene to give X, 2,3-dimethylbutadiene gives XI, and analogous compounds are formed with 1,1,3-trimethylbutadiene, cyclopentadiene, and 9-bromoanthracene. The structure of the adduct of 9-bromoanthracene may be inferred from that of the adduct XII, which is formed by combination of a second mole of anthracene with the initial adduct.



X



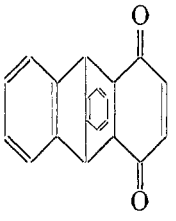
XI



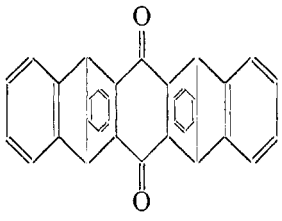
XII

The decomposition of X on heating is of interest in that it indicates that the 1:1 anthracene–acetylenedicarboxylic acid adduct is less stable than the 1:1 butadiene–acetylenedicarboxylic acid adduct, for anthracene and 3,6-dihydrophthalic acid are obtained. However, interaction between these two products occurs, so that phthalic acid and 9,10-dihydroanthracene are also found. The higher the operating temperature, the greater is the amount of interaction. Low-temperature decomposition is best favored by operating *in vacuo* (158).

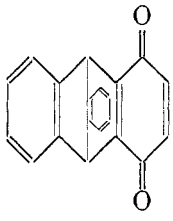
The addition of *p*-benzoquinone to anthracene yields two products. The first of them is XIII, which can add another mole of anthracene to yield the second product (XIV). Cautious oxidation of XIII yields 9,10-dihydro-9,10-endo-*o*-phenylene-1,4-anthraquinone (XV); more energetic oxidation gives 9,10-anthraquinone (107). In similar fashion, XIV may be oxidized to the corresponding tetrahydro-bis-endo-*o*-phenylenepentacenequinone.



XIII

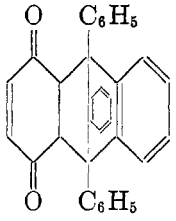


XIV

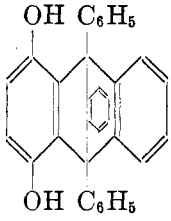


XV

The adduct (XVI) of equimolar quantities of 9,10-diphenylanthracene and *p*-benzoquinone isomerizes in part to give a hydroquinone (XVII), which combines with unchanged adduct to give a quinhydrone (107).



XVI



XVII

The reversibility of adduct formation of maleic anhydride with anthracene and certain of its derivatives has been studied from a quantitative standpoint (65, 66). As a reversible reaction, adduct formation obeys the law of mass action; accordingly, an increase in the concentration of one of the generators favors adduct formation. Further, an increase of temperature promotes dissociation as well as attainment of equilibrium. Table 9 gives equilibria attained in the reactions of maleic anhydride with anthracene and related compounds when dissolved in boiling xylene (138–140°C.). The effect of increase in the concentration of one of the generators is readily apparent.

The poor yield of the cholanthrene–maleic anhydride adduct may be improved by operating at a lower temperature (in boiling benzene), but the rate of attain-

ment of equilibrium is slower than in boiling xylene. If three mole proportions of maleic anhydride are used with benzene as solvent, the reaction is hastened and nearly quantitative yields of adduct are obtainable. The excess anhydride is easily separated from the adduct (65).

In connection with the diene reactions of the carcinogenic hydrocarbons 1,2,5,6-dibenzanthracene and 3-methylcholanthrene, the sodium salt of the maleic anhydride adduct of 1,2,5,6-dibenzanthracene is a water-soluble carcinogenic substance (66); and the same is probably true of the sodium salt of the corresponding 3-methylcholanthrene adduct, which was not reported as having been investigated in this respect.

While anthracene, its 9-phenyl, and its 9,10-diphenyl derivatives may be photoöxidized in carbon bisulfide solution, their maleic anhydride adducts are not photoöxidizable (188).

Other simple anthracene derivatives which add maleic anhydride are 9-bromoanthracene (75), 9-nitroanthracene (75), 9-carboxyaminoanthracene ethyl ester

TABLE 9

Equilibria attained in additions of maleic anhydride to anthracene derivatives in boiling xylene

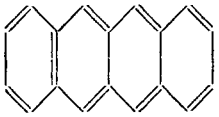
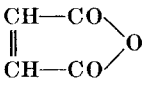
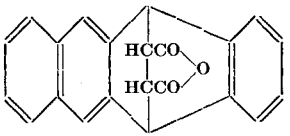
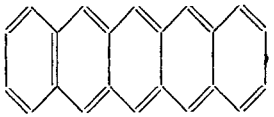
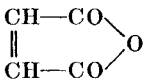
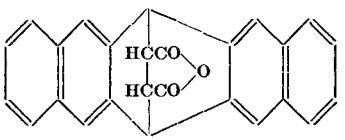
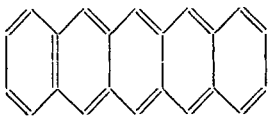
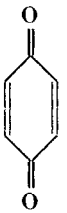
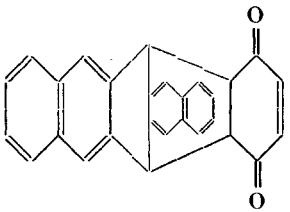
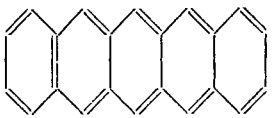
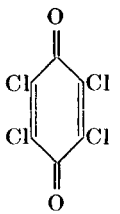
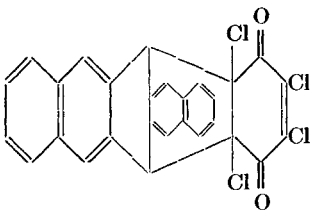
DIENE	PER CENT ADDUCT WITH 1 MOLE PROPORTION OF MALEIC ANHYDRIDE	PER CENT ADDUCT WITH 30 MOLE PROPORTIONS OF MALEIC ANHYDRIDE
Anthracene	99	
9-Methylanthracene	99	
9,10-Dimethylanthracene	98	
9-Phenylanthracene	75	97
9,10-Diphenylanthracene	16	78
1,2-Benzanthracene	84	99
1,2,5,6-Dibenzanthracene	32	83
3-Methylcholanthrene	22	
Cholanthrene	15	

(75), bis-9-anthrylamine (75), and 9-bromoanthracene-10-carboxylic acid (395). All additions occur normally in the 9- and 10-positions except for 9-aminoanthracene. 2-Chloroanthracene and 9,10-dichloroanthracene (108) also react normally with maleic anhydride. The 9,10-dichloroanthracene adduct reacts with benzene and aluminum chloride, giving 9,10-diphenylanthracene, possibly by the formation initially of the 9,10-diphenylanthracene–maleic anhydride adduct by the Friedel–Crafts reaction; this decomposes in part to give 9,10-diphenylanthracene and maleic anhydride. The last-named substance reacts with benzene and aluminum chloride to give benzoylacrylic acid. When *m*-xylene was substituted for benzene in this reaction (108), the product was 9,10-bis(4-*m*-xylyl)anthracene. Both arylated anthracenes were of the meso-form, a conclusion which might have been reached on the basis of the *cis* principle combined with the above mechanism (see the section on the stereochemistry of the diene synthesis, page 497).

β-Chloropropionic acid, by giving rise to acrylic acid *in situ*, reacts with

TABLE 10

Additions of dienophiles to polynuclear aromatics

HYDROCARBON	DIENOPHILE	ADDUCT	REFERENCE
			(66, 109, 386)
			(108)
			(107)
			(107)

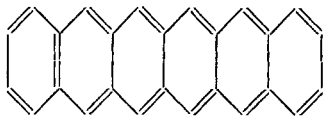
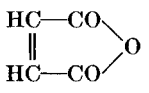
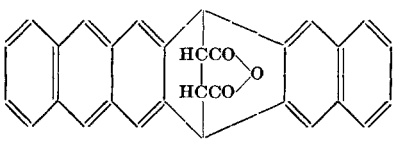
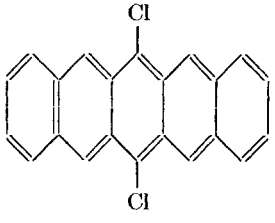
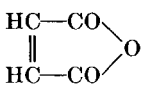
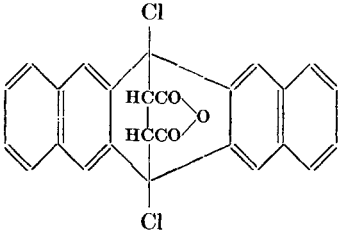
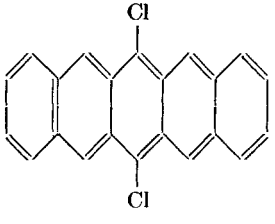
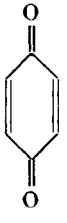
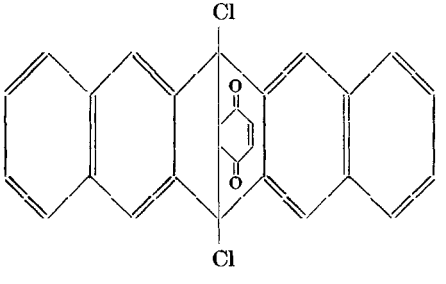
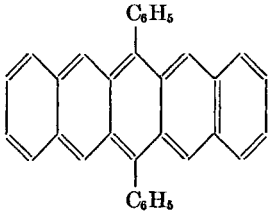
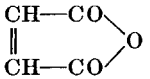
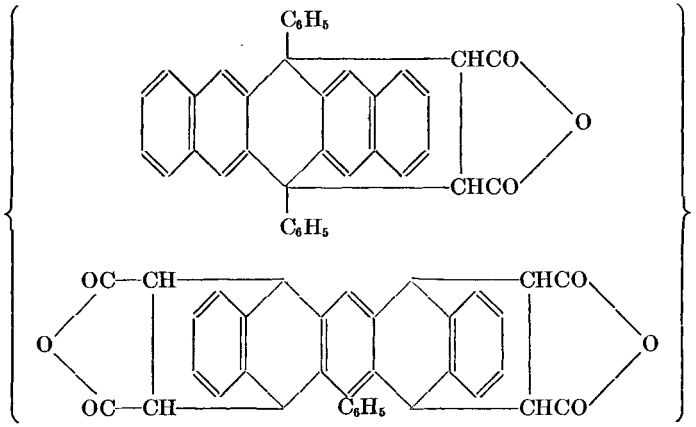
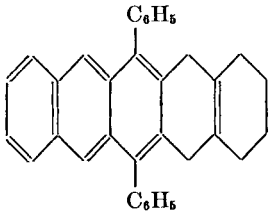
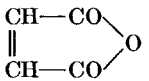
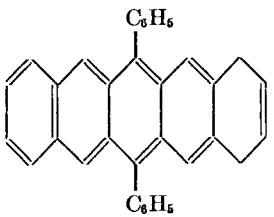
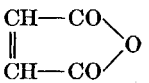
			(114)
			(109)
			(109)

TABLE 10—*Continued*

HYDROCARBON	DIENOPHILE	ADDUCT	REFERENCE
			(386)
		Adduct formed which reverts to generators on attempted isolation	(386)
		No reaction	(386)

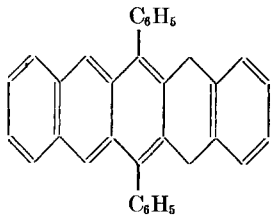
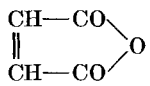
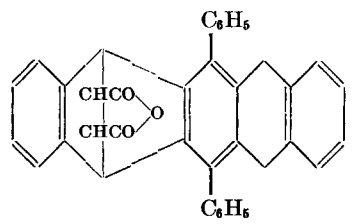
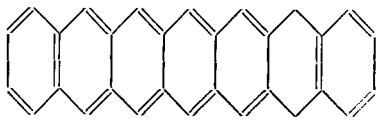
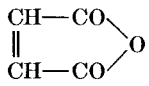
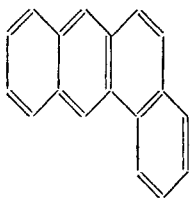
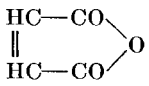
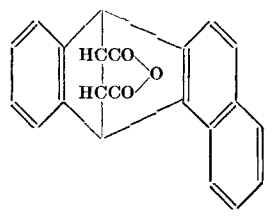
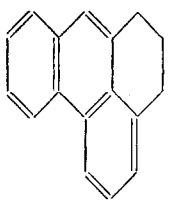
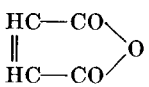
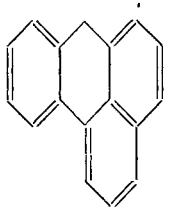
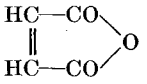
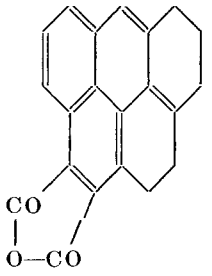
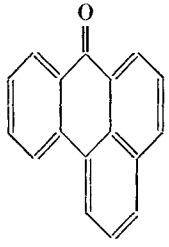
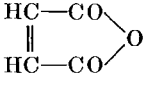
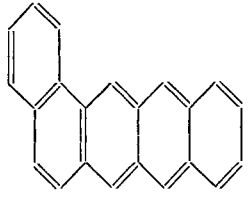
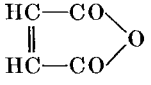
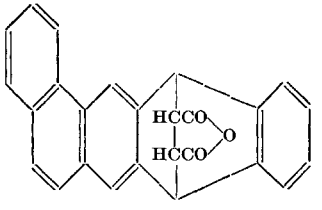
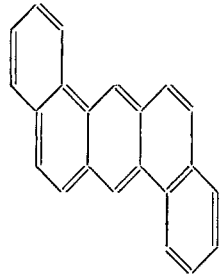
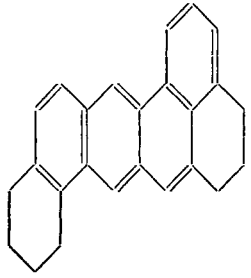
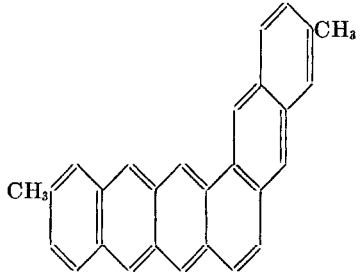
			(386)
		Reacts readily; product not isolated	(417)
			(66, 109)
		No reaction	(117)

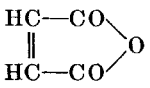
TABLE 10—*Continued*

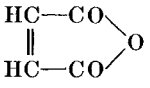
HYDROCARBON	DIENOPHILE	ADDUCT	REFERENCE
			(111)
		No reaction	(110)
			(120)

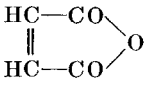


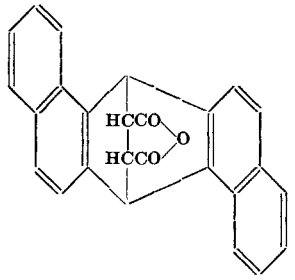




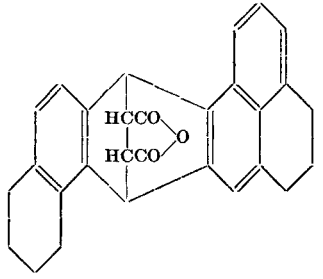




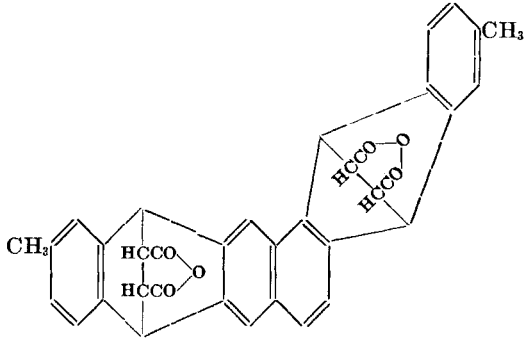




(66, 124)

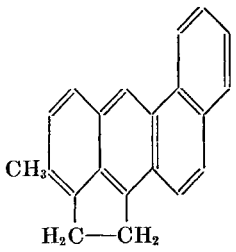
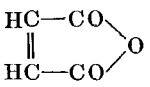
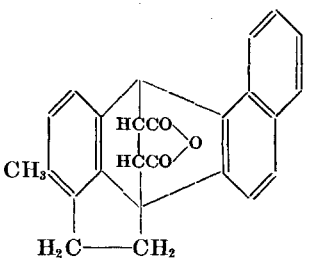
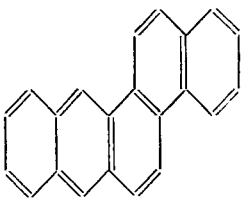
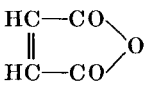
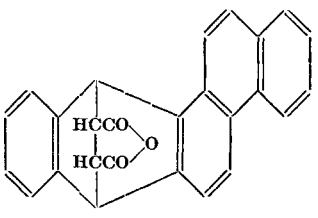
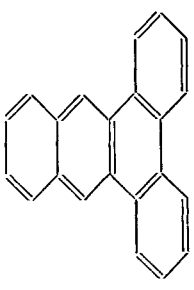
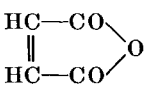
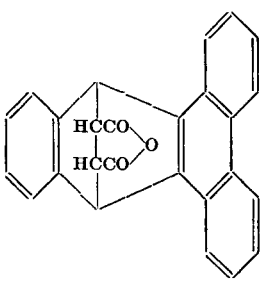


(116)



(108)

TABLE 10—*Continued*

HYDROCARBON	DIENOPHILE	ADDUCT	REFERENCE
			(66)
			(120)
			(120)

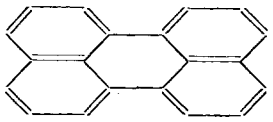
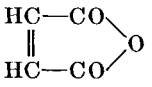
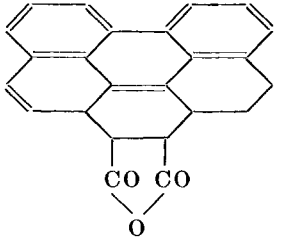
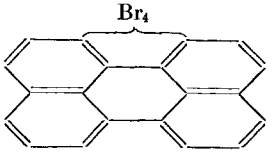
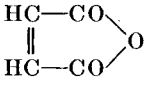
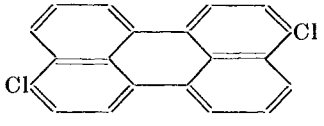
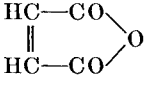
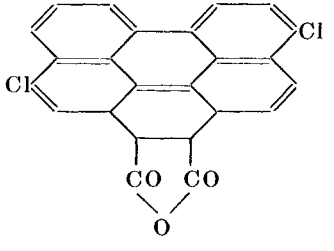
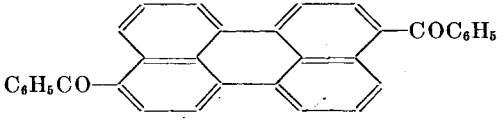
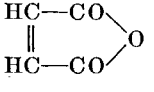
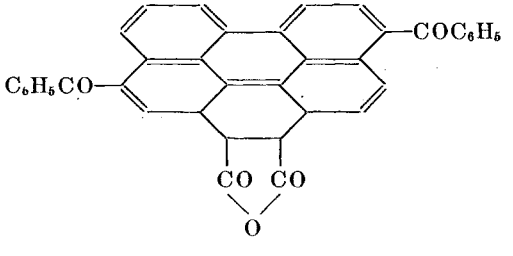
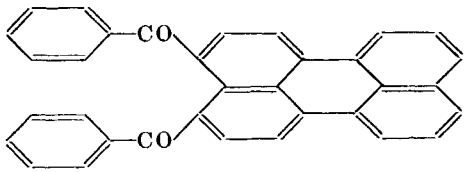
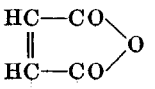
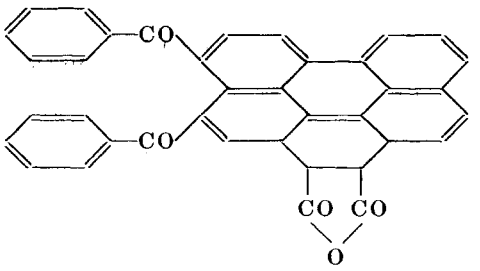
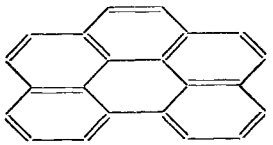
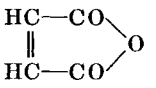
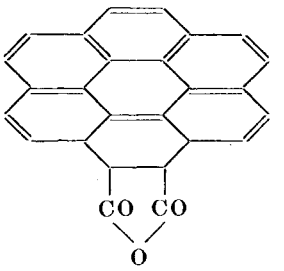
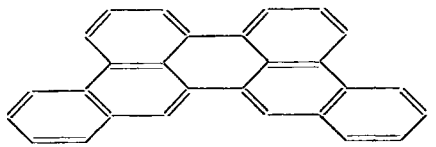
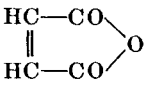
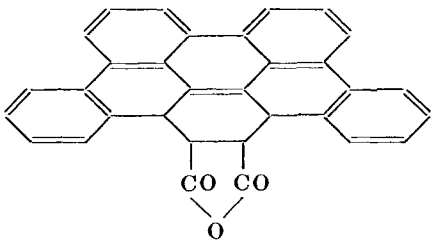
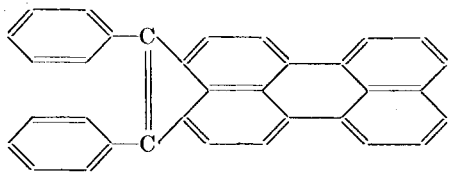
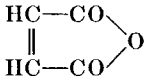
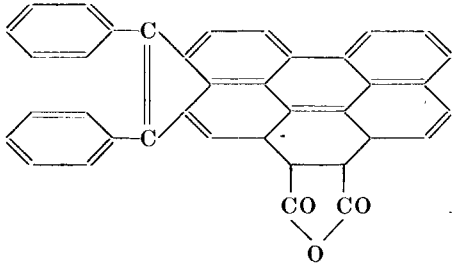
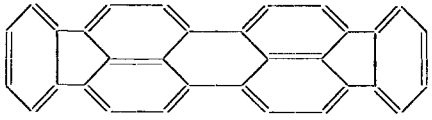
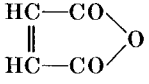
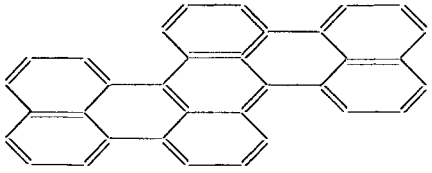
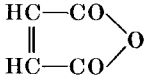
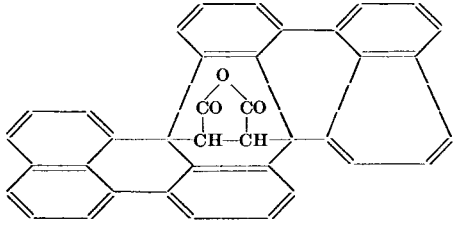
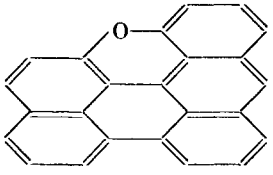
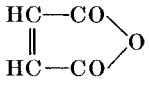
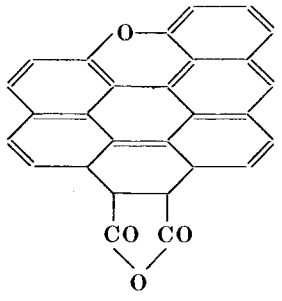
			(110, 115)
		No reaction	(377)
			(377)
			(377)

TABLE 10—*Continued*

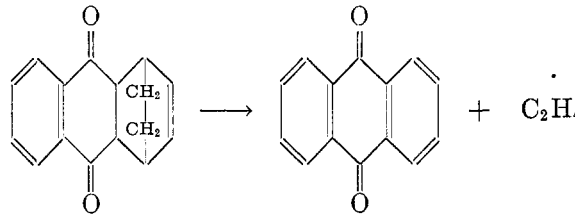
HYDROCARBON	DIENOPHILE	ADDUCT	REFERENCE
			(377)
			(110)
			(110)

			(377)
		No reaction	(95)
			(118)
			(115)

anthracene, 1,4-dimethylanthracene, and 9,10-dibromoanthracene as well as with 9,10-dichloroanthracene (73). With the exception of 9,10-dichloroanthracene, these compounds also add cinnamic acid.

9,10-Dibromoanthracene adds maleic anhydride at the 9- and 10-positions. The adduct is white, while the diene is yellow; hence a rough estimation of the progress of the addition may be made by noting the fading and eventual disappearance of the color. This diene does not appear to add acetylenedicarboxylic acid (149, 158).

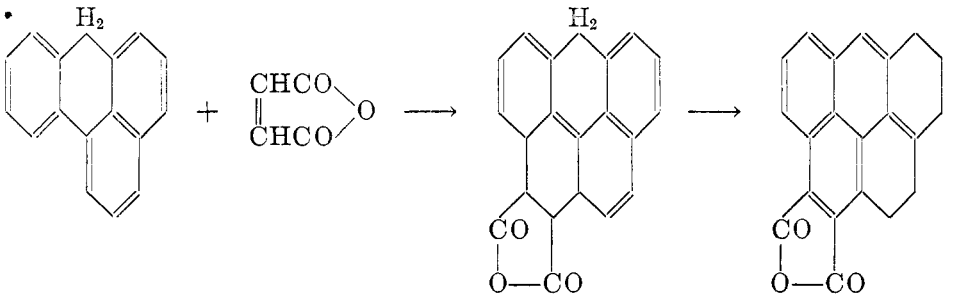
Although anthraquinone may be considered as possessing the grouping C=C—C=O, benzene rings are fused to each of these ethylenic double bonds, and this is sufficient to prohibit anthraquinone from acting as a dienophile. However, the carbonyl groups activate the benzene rings sufficiently so that anthraquinone may act as a diene (153). This is contrary to the observations of Morrell and Samuels (295), who were unable to observe addition of maleic anhydride to 9,10-anthraquinone. According to Diels, Alder, and their collaborators, the addition of maleic anhydride to 9,10-anthraquinone (153) takes place in the 1- and 4-positions. This is shown to be the case by decarboxylation of the adduct, which yields a compound identical with that obtained by addition of α-naphthoquinone to cyclohexadiene, in which adduct the endo bridge is known to be in the 1- and 4-positions. This substance pyrolyzes to ethylene and 9,10-anthraquinone.



It seems likely that the benzene rings of anthraquinone are not markedly different from those of naphthalene or benzene, and this assumption leads one to the prediction that these substances will add dienophiles which are unusually reactive and the adducts of which are, in general, of high stability toward heat. For example, an adduct of benzene and maleic anhydride might be expected to decompose into its generators when heated; similarly, an adduct of benzene and acetylenedicarboxylic ester might be expected to decompose into benzene, acetylenedicarboxylic ester, phthalic acid, and acetylene.

Phenanthrene has been examined for reactivity toward dienophiles (110, 291) and, as noted previously, no additions have been observed. The existence or non-existence of such additions are of importance in connection with the old question of the distribution of the fourth valence of carbon in aromatic compounds. The most recent analysis of the evidence for and against the various proposed structures is given by Fieser (203).

Benzanthrene adds maleic anhydride (111), but the initial adduct (XVIII) undergoes rearrangement under the experimental conditions employed.



XVIII

Higher polynuclear hydrocarbons in addition to those discussed above have been examined for reactivity with maleic anhydride or other dienophiles. Most of this work has been done by Clar and his collaborators, and is given in table 10.

XII. DIENE SYNTHESES BY AROMATIC HYDROCARBONS WITH UNSATURATED SIDE CHAINS

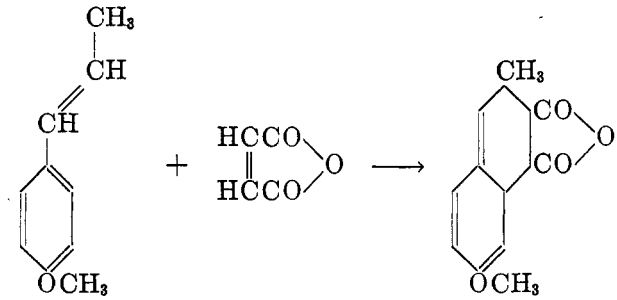
A. Vinylaromatics

The second type of polynuclear hydrocarbon to be considered is the type possessing an unsaturated side chain as substituent and acting as a diene toward dienophiles. Dienes which possess aromatic substituents will not be considered here, for they were discussed earlier. The compounds to be discussed are all homologs or benzologs of styrene and its derivatives; usually the parent aromatic hydrocarbons from which they are derived do not themselves add dienophiles, so that the mode of addition is apparent. In the addition of dienophiles by the styrene derivatives to be considered here, it is found that 1,4-addition occurs between the double bond of the unsaturated side chain and one of the Kekulé double bonds of the immediately adjacent benzene ring. A new double bond appears, which is semicyclic with respect to the former benzene ring which has now been converted into a 1,3-cyclohexadiene ring.

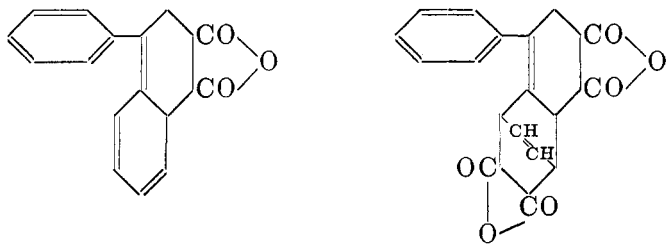
A tendency toward the addition of dienophiles according to the diene synthesis is possessed by styrene, which has been shown (*vide supra*) to possess dienophilic properties. Since butadiene, which usually acts as a diene, possesses dienophilic properties toward the cyclones (see cyclopentadienones) as well as toward itself, strict classification of compounds as dienes or dienophiles is sometimes difficult, and the case of styrene is one of the many examples of this problem.

One may recall that styrene polymerizes readily, and it may be that the diene synthesis plays an important part in this polymerization. Kuhn and Wagner-Jauregg (273) found that styrene adds an equimolecular quantity of maleic anhydride in boiling xylene solution. The product is polymeric; no monomeric adducts were found.

Despite the above report that no monomeric adduct is obtained from styrene and maleic anhydride, anethole (1-(*p*-methoxyphenyl)-1-propene) has been reported (289) to give an adduct with maleic anhydride which is monomeric (Hudson and Robinson (409) aver that the adduct is polymeric).



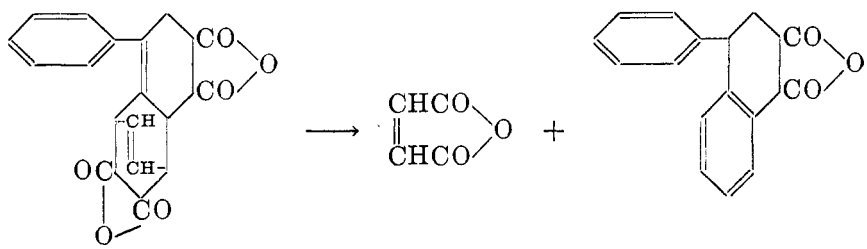
Since this adduct possesses a cyclohexadiene ring, it would be expected that a second mole of maleic anhydride could be added by the adduct. This reaction has not been reported, but in all probability will occur at higher temperatures. This expectation is realized in α-phenylstyrene (61, 346), which adds 2 moles of maleic anhydride, giving II. Presumably the compound I is formed as intermediate.



I II

The dienophilic property of a dienophile which adds to α-phenylstyrene must be rather pronounced, for citraconic anhydride does not add (see Class A dienophiles, page 327).

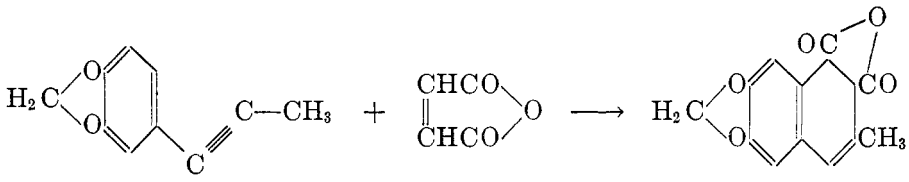
Adduct II is not particularly stable, for hydrogen bromide in acetic acid simultaneously splits out maleic anhydride and rearranges the double bonds.



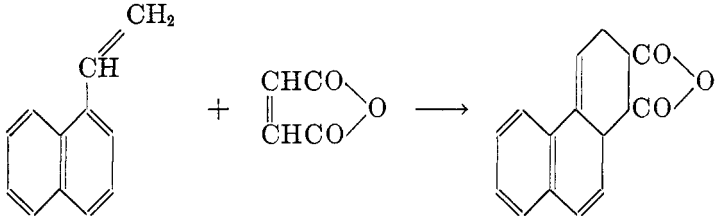
Hudson and Robinson (409) have made an extensive study of alkoxylated styrenes. Monomeric adducts are reported to form between isosafrole and maleic anhydride, diethyl maleate, and acetylenedicarboxylic ester. Isoeugenol also forms an adduct with diethyl maleate, as does its methyl ether. The ethyl ether of isoeugenol reacts normally with maleic anhydride to give 7-ethoxy-6-methoxy-3-methyl-1,2,3,4-tetrahydronaphthalene-1,2-dicarboxylic anhydride, but forms polymeric materials with diethyl maleate. In this connection it is to be noted that these authors report that the products obtained result from

double-bond wandering in the originally formed adducts. Certain other alkoxylated styrenes have been studied by these authors, who conclude that if a styrene is to form monomeric adducts, it must be substituted by an alkyl group in the β-position and be alkoxylated in a meta-position to the side-chain vinyl group, and this position must be para to the carbon atom which becomes the ring-fusion atom of the adduct. Alkoxylation in the para-position to the vinyl group facilitates adduct formation but is not necessary.

In this connection, methylene-3,4-dioxyphenylmethylacetylene adds maleic anhydride:

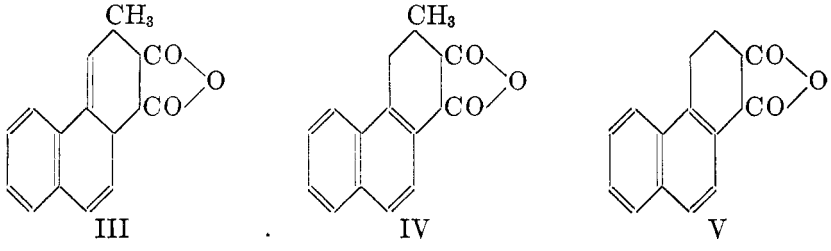


α-Vinylnaphthalene is capable of adding various dienophiles to give monomeric adducts. Since this occurs more easily than does the styrene addition, the naphthalene nucleus therefore exhibits a lower degree of aromaticity than does the benzene nucleus. One of the standards of aromatic character is the lack of ability of the compound under observation to add dienophiles. Arbuzov (61) did not observe any condensation of maleic anhydride with α-vinylnaphthalene, but others (67, 84, 123) were able to do so.

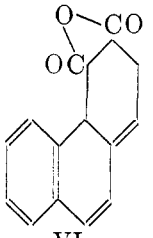


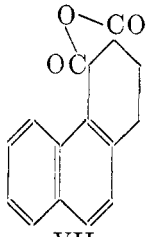
Arnold (389) reports that 5-vinyl- and 5-isopropenyl-hydrindenes polymerize in the presence of maleic anhydride. This appears to be analogous to the styrene reaction.

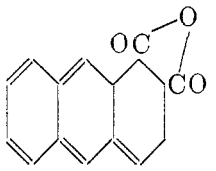
1-Propenylnaphthalene (206) does not add citraconic anhydride, but adds maleic anhydride to give III or IV. Fieser and Daudt are of the opinion that under the experimental conditions of this diene synthesis, wandering of a double bond of III occurs to give IV. This is not unlikely, but it has not been proved conclusively. If such is actually the case, then the adduct of 1-vinylnaphthalene and maleic anhydride has structure V instead of that given above.



β-Vinylnaphthalene adds maleic anhydride (123) in a manner which could have been predicted from the Mills–Nixon double-bond fixation theory. The product is 2,3,4,4a-tetrahydrophenanthrene-3,4-dicarboxylic anhydride (VI), but double-bond migration could have occurred, so that the supposed VI is actually 1,2,3,4-tetrahydrophenanthrene-3,4-dicarboxylic anhydride (VII). Formation of 1,1a,2,3-tetrahydroanthracenedicarboxylic anhydride (VIII) would be contrary to the Mills–Nixon hypothesis, and does not occur.

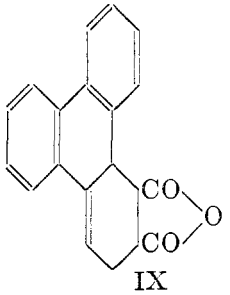

VI

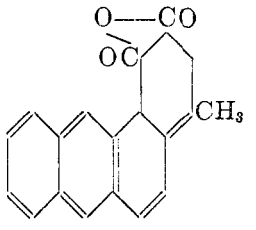

VII

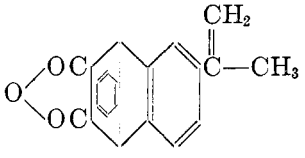

VIII

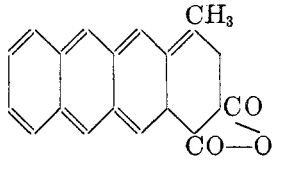
9-Vinylphenanthrene adds dienophiles to give partially hydrogenated derivatives of tri-*o*-phenylene. With maleic anhydride it gives IX. 9-Isopropenyl- and 9-(β-styryl)phenanthrenes form analogous products with maleic anhydride, but 9-(α-styryl)phenanthrene does not react. These styrylated phenanthrenes may be regarded as triarylated butadienes; it appears (84) to be a general rule that 1,2,3-triarylated butadienes do not add dienophiles, although the 1,1,2- and 1,2,4-isomers are capable of addition. Consequently α-(9-phenanthryl)-stilbene (87,393) does not add dienophiles.

The above examples were of simple vinylaromatics the parent aromatics of which do not add dienophiles. One case has been noted of a vinylaromatic the parent aromatic of which adds dienophiles. This is β-isopropenylanthracene (87), which could add maleic anhydride to give either X, XI, or XII. It adds but 1 mole of maleic anhydride.


IX

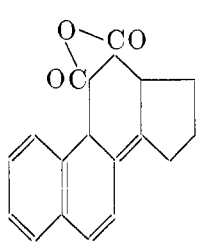

X

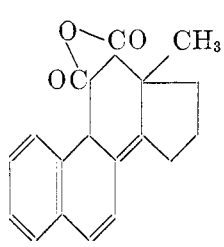

XI

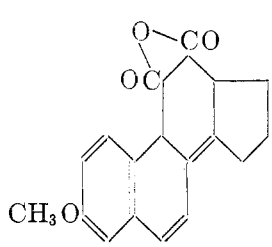

XII

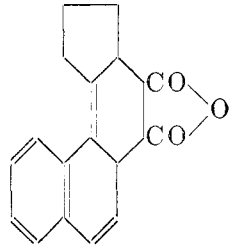
The adduct is not likely to be XII, for formation of such a product would be contrary to the Mills–Nixon hypothesis. The product is believed (87) to be XI.

Certain alicyclic derivatives of α- and β-vinylnaphthalenes have been investigated. A typical substance of this type is β-(1-cyclopentenyl)naphthalene, which adds maleic anhydride (67) to give a partially dehydrogenated sterol derivative (XIII). β-(2-Methyl-1-cyclopentenyl)naphthalene gives XIV; 6-methoxy-2-(1-cyclopentenyl)naphthalene gives XV; and α-(2-methyl-1-cyclopentenyl)naphthalene (67) gives XVI. On the other hand, α-(1-cyclohexenyl)-naphthalene (87) does not add maleic anhydride, though Bachmann and Kloetzel (67) reported the occurrence of a reaction.


XIII


XIV

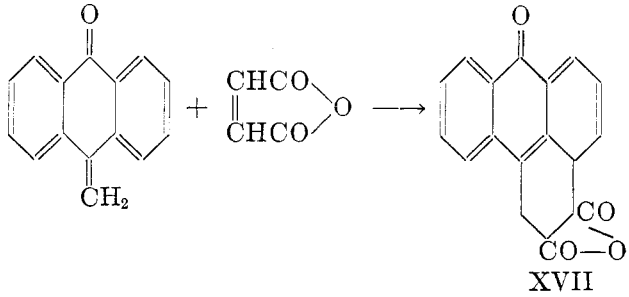

XV

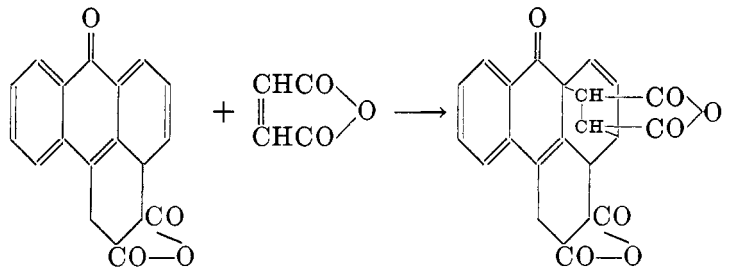

XVI

The above vinylnaphthalene derivatives which are methylated in the 2-position of the cyclenyl group add dienophiles more slowly than do their unmethylated parent compounds, for angular methyl groups appear in the adducts of the methylated vinylnaphthalene derivatives. The unmethylated cyclenylnaphthalenes add dienophiles with nearly the same ease as does vinylnaphthalene. Bachmann (67) used these compounds to synthesize the sterol-ring structure. Only one structure is possible for the final ring system when β-(1-cyclenyl)naphthalenes are used; this is an advantage not possessed by certain other syntheses of the sterol-ring system by the diene synthesis.

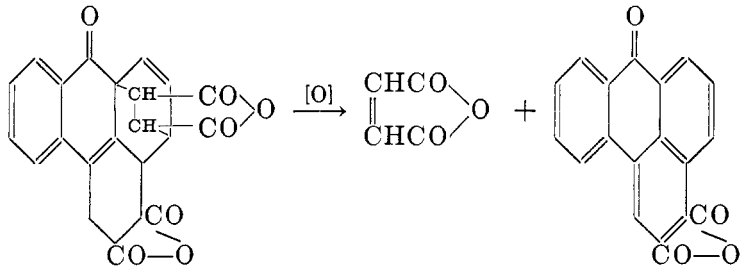
B. 9-Methyleneanthrone and derivatives

9-Methyleneanthrone and its derivatives add dienophiles readily to give partially hydrogenated derivatives of benzanthrones (113). In many cases these products are easily oxidized, often by atmospheric oxygen, to give benzanthrone derivatives (113). It is often found, therefore, that the products isolated from diene syntheses employing these methyleneanthrone derivatives are completely aromatic rather than hydroaromatic. It is sometimes found that 2 moles of dienophile add to the benzanthrone derivative, the second mole being regenerated when the product so obtained is oxidized to the benzanthrone derivative. This is illustrated by the reaction of methyleneanthrone with maleic anhydride (113), which proceeds in acetic acid solution according to the scheme


XVII



XVIII



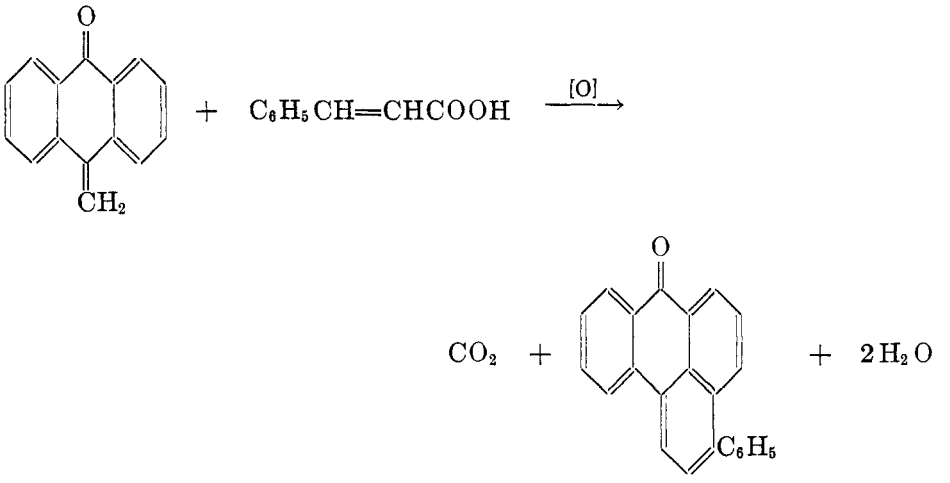
XIX

The initial adduct (XVII) contains the cyclohexadiene ring, and therefore is capable of addition of the second mole of maleic anhydride to give XVIII. Oxidation of XVIII yields maleic anhydride and XIX. If the generators are fused together in the presence of air or with an oxidizing agent or solvent (251), addition and dehydrogenation occur simultaneously; upwards of 50 per cent yields of XIX are obtained.

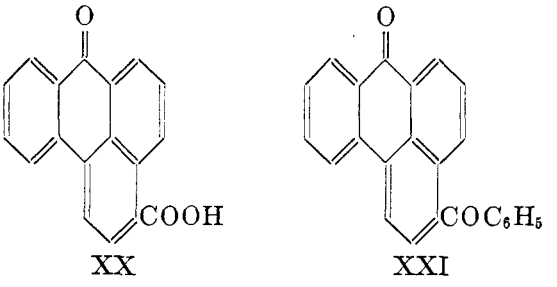
The I. G. Farbenindustrie A.-G. owns a patent (251) which covers the additions of the following dienophiles to methyleneanthrone: maleic anhydride, cinnamic acid, ethyl cinnamate, fumaric acid, crotonaldehyde, benzalacetophenone, stilbene, butadiene, and β-chloropropionic acid (which reacts by forming acrylic acid *in situ*). All additions are conducted in the presence of an oxidizing agent or solvent, usually nitrobenzene. As a result, the hydroaromatics originally formed are dehydrogenated, and the products isolated from the reaction mixtures are completely aromatic.

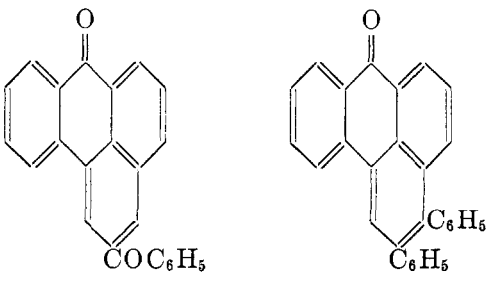
This dehydrogenating action of nitrobenzene is rather general. Bergmann (394) has obtained 3,6-diphenylphthalic anhydride by boiling 3,6-diphenyl-1,2,3,6-tetrahydrophthalic anhydride with nitrobenzene. The method has its limitations, as pointed out by Bergmann. *m*-Dinitrobenzene, *p*-chloronitrobenzene, and *p*-bromonitrobenzene exhibited no dehydrogenating effects at 140°C. or lower; apparently higher temperatures were not tried. The usual operating temperature range for nitrobenzene is 200–250°C.

Addition of cinnamic acid (113, 251) to methyleneanthrone in boiling nitrobenzene gives *Bz*-1-phenylbenzanthrone, decarboxylation occurring during the synthesis.

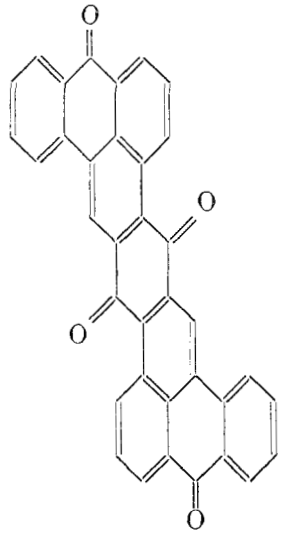


A similar decarboxylation occurs in the addition of fumaric acid, the product being XX. Benzoylethylene (47) gives what is believed to be XXI; structure XXII for the product is less likely but not impossible. Stilbene (47) gives XXIII.

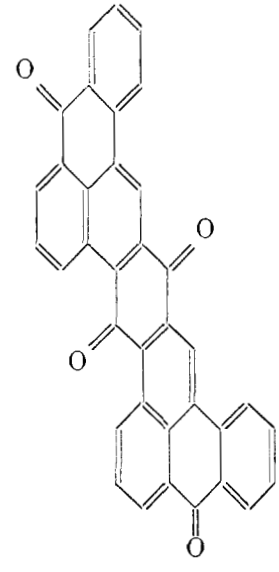




Methyleneanthrone also adds quinones. When excess methyleneanthrone reacts with *p*-benzoquinone (113), atmospheric oxidation of the initial product results in the formation of bis-(benzanthrono-*Bz*-1,2)-2,3,5,6-*p*-benzoquinone (XXIV). Clar appears to have overlooked the possibility of an unsymmetrical structure (XXV) for the product.

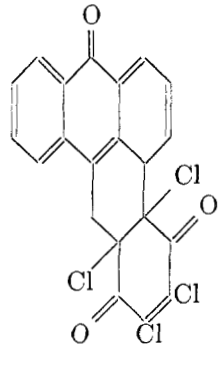


XXIV

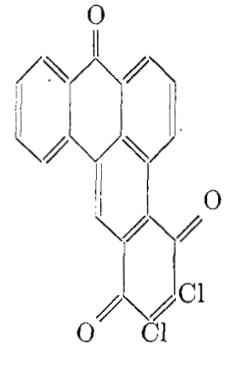


XXV

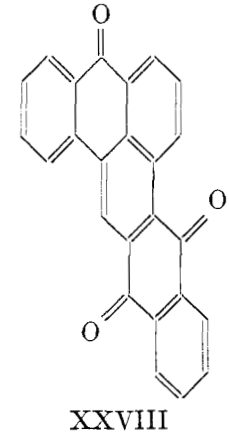
When chloranil and methyleneanthrone react, the oxidation step is unnecessary, since this was accomplished during the chlorination of the quinone. Elimination of hydrogen chloride from the initial product (XXVI) gives XXVII. Addition of excess methyleneanthrone to chloranil results in the loss of hydrogen chloride and formation of the same product that is obtained by the oxidative addition of methyleneanthrone to *p*-benzoquinone, XXIV or XXV.



XXVI



XXVII

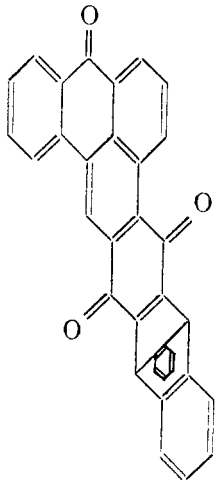


XXVIII

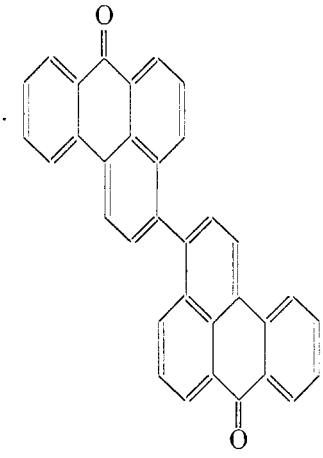
Interaction of air, methyleneanthrone, and α-naphthoquinone gives (XXVIII). This product might also be formed by reaction of butadiene with XXVII, followed by dehydrochlorination of the resulting product.

9,10-Dihydro-9,10-*o*-phenylene-1,4-anthraquinone (prepared by addition of 1 mole of anthracene to 1 mole of *p*-benzoquinone, followed by gentle oxidation

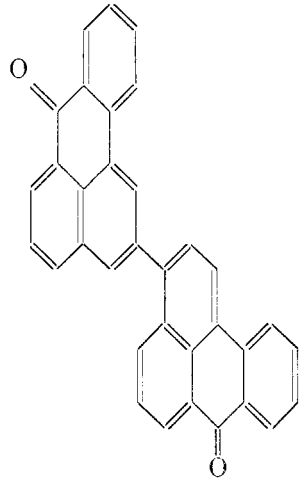
of the adduct) adds to methyleneanthrone in the presence of air to give XXIX as the final product. The structure of the butadiene adduct (251) with methyleneanthrone is given as XXX, although other structures such as XXXI do not appear to have been excluded from consideration. The symmetrical nature of XXX is the sole advantage of that structure.



XXIX



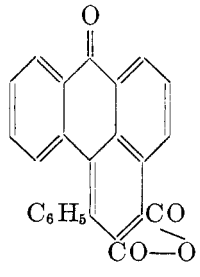
XXX



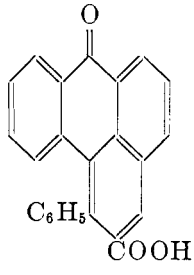
XXXI

ω-Phenylmethyleneanthrone (benzylideneanthrone) adds dienophiles (112, 113); with maleic anhydride, XXXII is formed in the presence of air, while fumaric acid forms what is thought to be XXXIII, decarboxylation occurring in the *Bz*-1-position. It will be recalled that in the additions of fumaric and cinnamic acids to methyleneanthrone itself, decarboxylation was postulated as occurring in the *Bz*-2-position of the initial or oxidized adducts.

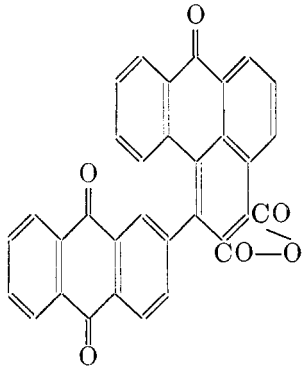
ω-(2-Anthraquinoyl)methyleneanthrone (112, 113) reacts with maleic anhydride and air to give XXXIV.



XXXII



XXXIII



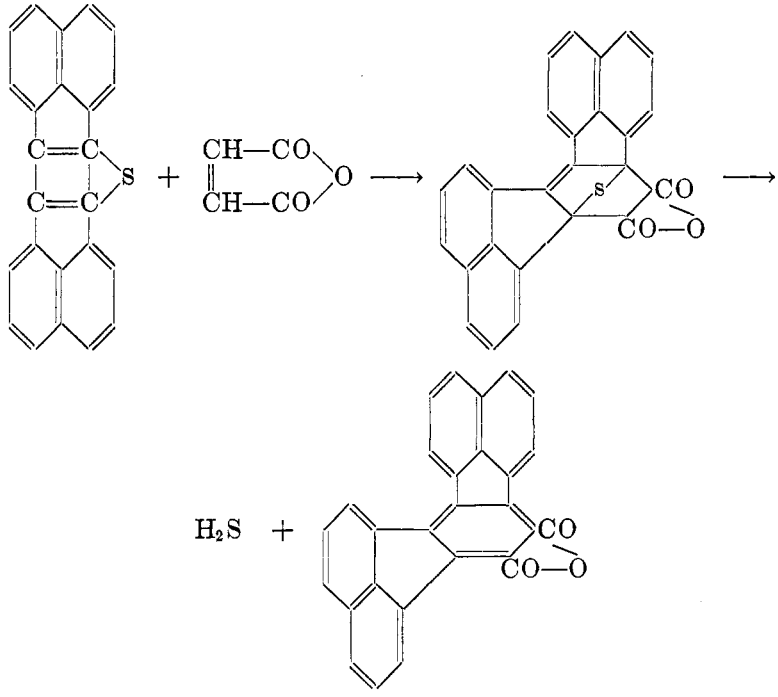
XXXIV

XIII. HETEROCYCLIC DIENES

A. Thiophene and derivatives

Thiophene is closely related to benzene and furan. Like benzene, thiophene is stated not to add dienophiles (135), and the same probably applies to homologs such as the thiotolenes and thioxenes. Thionessal does not add dienophiles (400). Also, even though the isobenzofurans add dienophiles, the isobenzothiophenes do not (186). It is also likely that the selenophenes do not add dienophiles.

Reinvestigation of the above may result from the recent work of Clapp (400), who was able to add maleic anhydride to 2,3,4,5-bis(1,8-naphthalene)thiophene at 255°C., obtaining 3,4,5,6-bis(1,8-naphthalene)phthalic anhydride. The hypothetical addition product apparently lost hydrogen sulfide to yield the substituted phthalic anhydride:



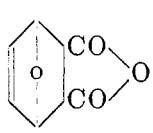
B. Furan and derivatives

Furan contains the conjugated-double-bond system required of dienes which undergo the diene synthesis. Indeed, the most extensively studied of the dienophiles (maleic anhydride) may be regarded as the quinone of furan (301). Like the aromatic quinones, it forms colored complexes with polynuclear aromatics, phenols, and arylamines, and responds to the triphenylphosphine test (326, 327) for quinones. Its addition of dienes resembles those of quinones; however, diene addition is by no means a property peculiar to quinones, especially since many quinones, such as anthraquinone, do not add dienes. Anthraquinone

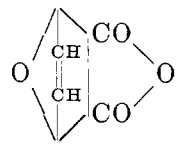
is the lowest benzolog of *p*-benzoquinone possessing benzene rings fused to each of the two carbonylenic double bonds. The lowest benzolog of furanquinone is phthalic anhydride, which also does not add dienes.

Except under certain highly restricted conditions, the addition of dienophiles by furan and its derivatives results in what is termed an oxygen bridge. Thus furan and maleic anhydride react to give I, possessing the oxygen bridge.

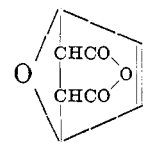
In the study of the usual two-dimensional structural pictures of these and other bridged compounds, care must be taken to avoid the impression that a so-called bridge possesses extraordinary and unique properties. A three-dimensional model of a bridged compound shows that such an assumption is invalid and that, save for convenience in nomenclature, there is no reason for stating that one or another group of atoms forms the bridge, and that the remainder of the molecule is more like the common simple compounds. Thus the furan-maleic anhydride adduct may be represented by three structures:



I

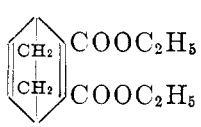


II

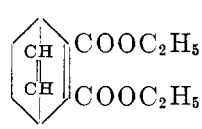


III

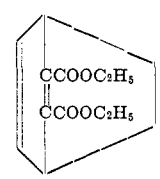
It should always be kept in mind that the bridge, as such, does not confer special properties on the atoms included in that bridge, although the natural human tendency appears to be that one will tend to place the more reactive portion of the molecule in the bridge on drawing the structure of such a bridged compound. The tendency is shown in the papers of Diels, Clar, Dane, Butz, Alder, Fieser, and many others. Oftentimes it is most convenient to place the most reactive portion of the molecule in the bridge, for it is usually smaller (from the point of view of writing the structures) than the less reactive portions of the molecule. Though the adduct of cyclohexadiene and acetylenedicarboxylic ester splits out ethylene on heating, it is no less correct to write its structure as V or VI as well as IV, which is the usual notation.



IV



V



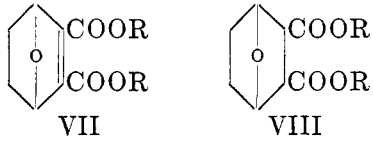
VI

For convenience, however, the usual methods of structure designation and nomenclature of bridged compounds have been followed in this paper. Hence in discussion of adducts of furan and related compounds, reference will be made to the oxygen bridge, though it is no more of a bridge than other portions of the molecule under consideration.

The oxygen bridge is thermodynamically stable in most respects, particularly so toward heat. Heating of furan adducts almost invariably results in resolution

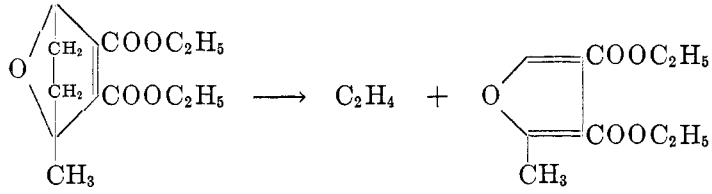
into their generators or else into pyrolytic decomposition products of these generators. Occasionally decomposition occurs in other portions of the molecule, but the oxygen bridge is almost never ruptured by heat alone (14, 146).

The adducts of the furans with acetylenedicarboxylic esters or the acid itself may be hydrogenated in stages (10, 166), first giving VII and eventually VIII.

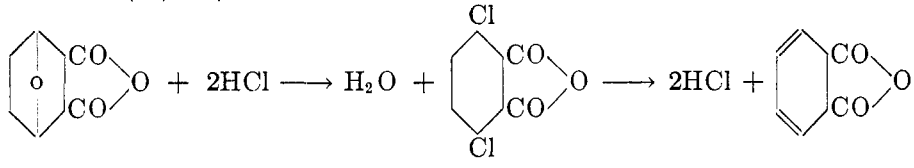


VII VIII

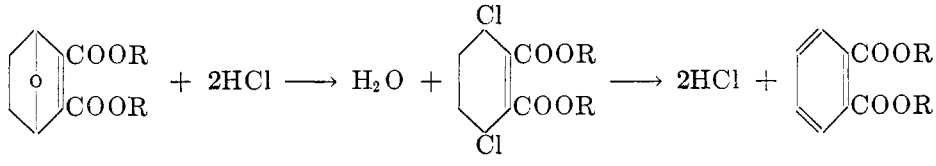
The partially hydrogenated adduct of sylvan (α-methylfuran) and acetylenedicarboxylic ester, corresponding to VII in structure, evolves ethylene on heating (14) and forms 2-methyl-3,4-furandicarboxylic ester:



The partially or fully hydrogenated adducts of acetylenedicarboxylic ester and other acetylenic dienophiles with furans and also the hydrogenated adducts of ethylenic dienophiles with furans are attacked by hydrogen chloride or bromide to open the oxygen bridge. That this is reasonable may be seen when it is noted that such hydrogenated adducts are derivatives of tetramethylene oxide, the ring of which may be ruptured by treatment with hydrogen halides to give tetramethylene halides. When the bridge carbon atoms (those to which the oxygen bridge is attached) possess alkyl or aryl substituents, the dihalo compound which results by action of hydrogen halides usually dehydrohalogenates spontaneously to give cyclohexadiene derivatives. When no such substituents are present, the dihalo compound usually can be isolated, but only slight heating is necessary to cause dehydrohalogenation and formation of the cyclohexadiene derivative (14, 146):

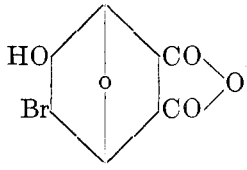


Similar treatment of the partially hydrogenated adducts of the furans with equimolar quantities of acetylenic dienophiles (14, 146) yields benzene derivatives:

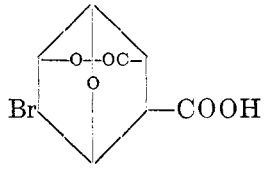


The action of hydrogen halides on the unhydrogenated adducts has not been reported, but it would most likely give a mixture of derivatives of phenol and halobenzene.

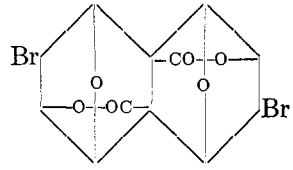
The adduct of furan and maleic anhydride will add hypobromous acid to give a compound (IX) which lactonizes easily, yielding X. This lactone acid is sensitive to hydrogen halides, for hydrogen bromide ruptures the bridge and simultaneous dehydration and dehydrohalogenation result in the formation of phthalic acid (14). In like manner, the adduct of 2 moles of furan with 1 mole of acetylenedicarboxylic acid will form a monolactone and eventually a dilactone (XI) with hypobromous acid (166).



IX

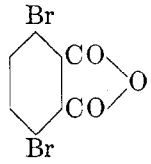


X

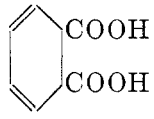


XI

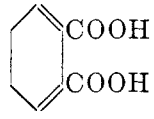
It may be seen that certain of the above reactions are adaptable to the preparation of 1,3-cyclohexadiene. The reduced adduct of furan and maleic anhydride (VIII), which is also formed by complete reduction of the adduct of equimolar quantities of furan and acetylenedicarboxylic acid, may be treated with hydrogen bromide and the resulting compound (XII) dehydrobrominated to give a cyclohexadienedicarboxylic acid (XIII or XIV). This may be decarboxylated to yield 1,3-cyclohexadiene. Oxidation of the dicarboxylic acid, which is either XIII or XIV, yields phthalic acid. Similar reaction sequences are shown by substituted furans, and the method offers means of preparing substituted



XII



XIII



XIV

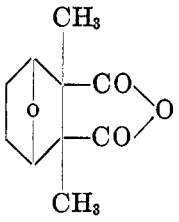
cyclohexadienes. Examination of the adducts of the substituted cyclohexadienes should offer circumstantial evidence which will permit a tentative choice between formulas XIII and XIV.

When working with the fully hydrogenated adducts of furans and maleic anhydride, one should bear in mind that these materials are vesicant (146, 148).

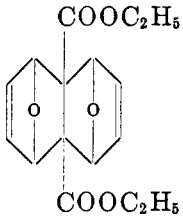
The additions of furan to maleic anhydride (146, 148, 166), acetylenedicarboxylic ester (148, 166), and pyrocinchonic anhydride (135, 146) have been studied. It is of interest to note that the addition of pyrocinchonic anhydride could not be repeated (166) nor could α-methyl-β-chlorocrotonic acid (166) be added to furan. In the earlier work on pyrocinchonic anhydride additions, it was reported that cantharadin (XV) was synthesized by reduction of the double bond of the pyrocinchonic anhydride adduct.

The adduct of equimolar quantities of furan and acetylenedicarboxylic ester

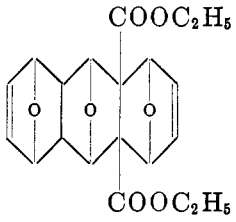
will add a second and even a third mole of furan to give XVI and XVII, respectively (166).



XV

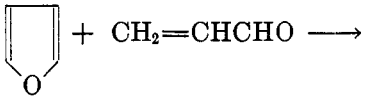


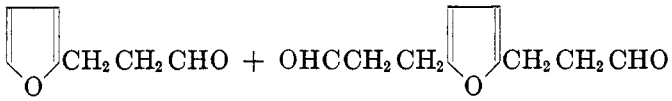
XVI



XVII

It has been found that in the presence of traces of sulfur dioxide, furan will not add acrolein according to the diene synthesis (89, 330). The reaction, which occurs only to a moderate extent, is:

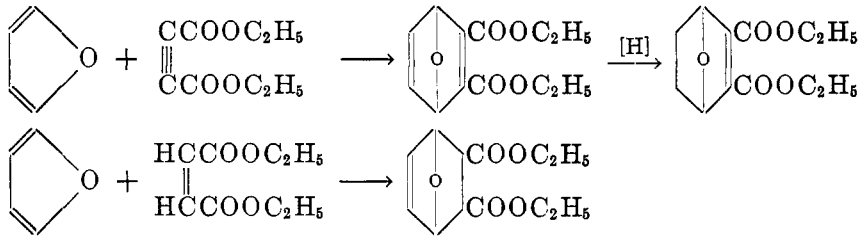




In a typical experiment, 146 g. of dry furan and 120 g. of dry acrolein were heated at 100°C. for 1 hr. with 10 mg. of sulfur dioxide dissolved in 0.5 ml. of water. Half a gram of hydroquinone had been added to stabilize the acrolein. The object of using dried materials is not known, since aqueous sulfur dioxide was used. The reaction product was 17 g. of the monoaldehyde and 30.5 g. of the dialdehyde. The reaction does not occur in the absence of sulfur dioxide or in the presence of other acidic compounds. Thus, acrylic acid gives polyacrylic acid and unchanged furan under these conditions. Further, sulfur dioxide does not catalyze the combination of some other olefinic aldehydes with furan in this manner.

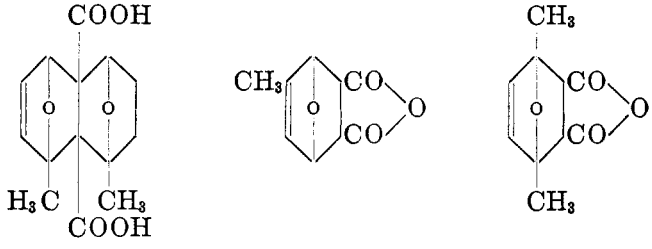
It will be shown later that this reaction of furan with acrolein is similar in type to certain reactions of pyrroles with dienophiles.

Sylvan (2-methylfuran) reacts with acetylenedicarboxylic esters and maleic anhydride and esters in the same way as does furan (9, 308). Hydrogenation of the acetylenedicarboxylic ester adducts of both furan and sylvan, using palladium and hydrogen, results in the initial reduction of one double bond so as to give 3,4,5,6-tetrahydro-3,6-endo-oxo-phthalic anhydride. It will be noted that the active double bond of these adducts is located in a position analogous to that of the cyclopentadiene–acetylenedicarboxylic ester adduct. The furan– or sylvan–acetylenedicarboxylic ester adducts are, when partially reduced, isomeric with the corresponding unreduced adducts with maleic (or fumaric) ester:



The partially hydrogenated adducts of acetylenedicarboxylic esters with furan or sylvan contain the grouping C=C—C=O; like the unhydrogenated adducts, they are able to add dienophiles. The dienophilic property is present to much the same degree as in allyl chloride (page 333), since addition of butadiene to these compounds requires a temperature of the order of 170°C. Dehydration occurs simultaneously when the original acetylenic dienophile is acetylenedicarboxylic acid, so that the product is an anhydride of an acid containing angular carboxyl groups. When sylvan is added to the partially reduced adduct of equimolecular quantities of sylvan and acetylenedicarboxylic acid (9), the product is XVIII or the isomer with opposed methyl groups.

3-Methylfuran (308) has been observed to add maleic anhydride to give XIX. 2,5-Dimethylfuran adds maleic anhydride to give XX. The reduced adduct from XX is attacked by hydrobromic acid to give 3,6-dimethyl-1,2-dihydro-



XVIII XIX XX

phthalic acid. The intermediate dihalo compound could not be isolated under the conditions of the experiment (146). Decarboxylation of the dimethyldihydrophthalic acid yields 1,4-dimethyl-1,3-cyclohexadiene. The formation of these compounds may give a clue as to the formula of the dihydrophthalic acid obtained by the action of hydrobromic acid on the reduced adduct of furan and maleic anhydride. It would appear that the dihydrophthalic acid is XIII rather than XIV. The dimethyldihydrophthalic acid may be oxidized by nitric acid to give 3,6-dimethylphthalic acid (146).

2,5-Dimethylfuran reacts with acetylene in a manner similar to certain pyrrole reactions to give acetonylideneacetone.

2-Methyl-5-isopropylfuran (97) has been observed to react with maleic anhydride. The reaction has been employed for the synthesis of cineole.

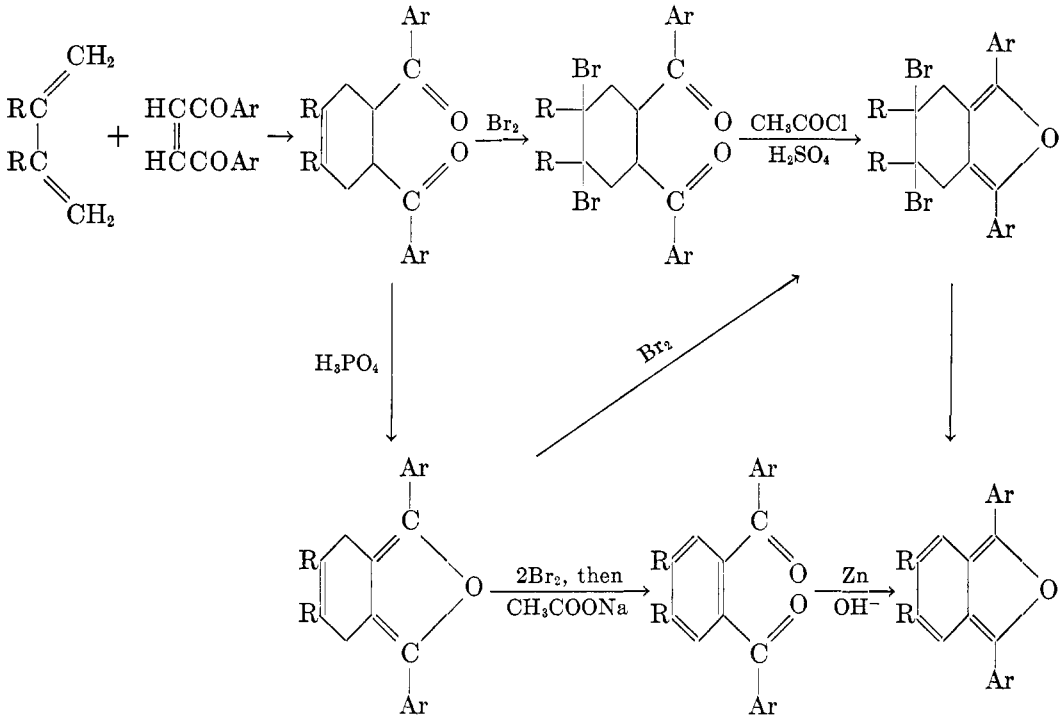
Furyl acetate is also capable of addition of dienophiles (147). The addition of maleic anhydride yields 3-acetoxymethyl-3,6-endo-oxo-1,2,3,6-tetrahydrophthalic anhydride.

2-(β-Phenylethyl)furan adds maleic anhydride (373) to give an adduct which dissociates in solution with great ease, and must be purified by crystallization at low temperatures. When the above adduct is heated on a steam bath in a current of nitrogen, dissociation takes place to such an extent that 2-(β-phenylethyl)furan sublimes. Similar properties are shown (373) by the maleic anhydride adduct of 2-β-(*m*-methoxyphenyl)ethylfuran.

2-(2-Tetrahydrofurfuryl)furan (271) has been observed to add maleic anhydride. Benzoylethylene (47) does not appear to add to furan, sylvan, or 2,5-dimethylfuran.

C. Isobenzofurans

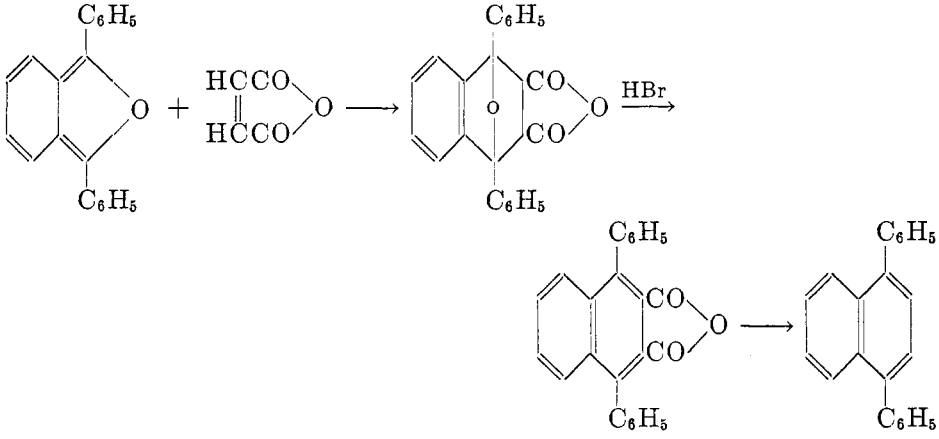
The isobenzofurans are conveniently prepared (3,6) by a diene synthesis. A symmetrical diaroylethylene is added to a simple diene to give an adduct which is then dehydrated and rearranged into a substituted dihydroisobenzofuran. The complete picture of the reactions involved is as follows:



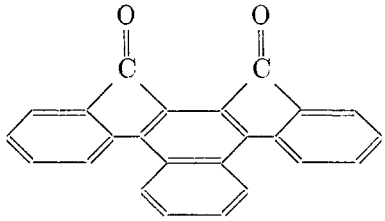
In this series of reactions, R is either hydrogen or methyl, while Ar may be phenyl, *p*-chlorophenyl, *p*-tolyl, 2-mesitylenyl, α-naphthyl, *p*-xenyl, or 3,5-dibromo-4-hydroxyphenyl (3, 4, 6, 355, 356). A portion of this series has been conducted using cyclopentadiene (3). 2,3-Dimethylbutadiene did not react when Ar was 2-mesitylenyl (6).

The resulting isobenzofurans will add various dienophiles. The outstanding

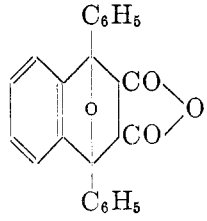
characteristic of the resulting adducts is their ease of dissociation into their generators, which will be illustrated later with specific examples. The adducts are, however, of great synthetic value. Dufraisse and Priou (187) prepared 1,4-diphenylnaphthalene by the following series of reactions:



Weiss and his coworkers (353) employed the 1,4-diphenyl-2,3-naphthalic anhydride obtained as an intermediate in the above series of reactions in the synthesis of a difluorenone. The naphthalic anhydride cyclized in the presence of sulfuric acid to give *sym*-1,2,3,4-*o*-dibenzoylenenaphthalene (XXI).



XXI

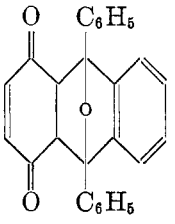


XXII

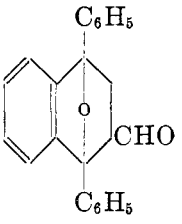
Barnett (71) added maleic anhydride to 1,3-diphenylisobenzofuran to obtain XXII. This reaction proceeds at room temperature in a dichloroethylene solution of the reactants. According to Dufraisse and Priou (188), the adduct obtained at higher temperatures differs from that obtained at room temperature, though both adducts undergo hydrolysis to give the same acid. The room-temperature adduct is stable in the solid state, but dissociation takes place in solvents such as ethyl acetate with formation of limited amounts of the generators. It is indeed remarkable that the aromatic ring of the adduct should revert spontaneously to the cyclohexadiene ring of the isobenzofuran, and especially to a diene containing semicyclic double bonds which ordinarily tend to wander into the ring. Considerations such as these may lead one to wonder if the diene addition reaction has not occurred by some other mechanism, but the degradation of the adduct to 1,4-diphenylnaphthalene by Dufraisse and Priou (187) indicates that such is not the case.

p-Benzoquinone also combines with 1,3-diphenylisobenzofuran to give XXIII which is stable in the solid state, but which dissociates in solution to such a considerable degree that purification by crystallization is difficult (71). Action of hydrogen chloride should give 9,10-diphenyl-1,4-anthraquinone.

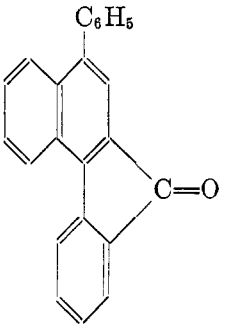
Acrolein was added to 1,3-diphenylisobenzofuran by Weiss and his coworkers (353). When the adduct (XXIV) was treated with an acetone solution of potassium permanganate, the oxide bridge was ruptured and the aldehyde group was oxidized, so that the final product was 1,4-diphenyl-2-naphthoic acid. Heating with soda lime partially decarboxylated the acid to 1,4-diphenylnaphthalene, but a substantial portion cyclized to 3-phenyl-1,2-benzofluorene (XXV).



XXIII

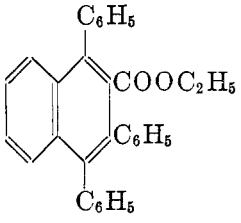


XXIV

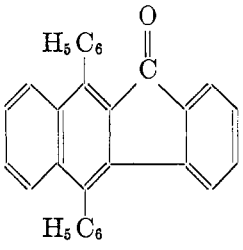


XXV

The reactions of diene synthesis and oxide-bridge rupture may be conducted in one operation (354). Addition of ethyl cinnamate to 1,3-diphenylisobenzofuran in a medium of alcoholic hydrogen chloride yields 1,3,4-triphenyl-2-naphthoic ethyl ester (XXVI), which is cyclized by sulfuric acid to 1,4-diphenyl-2,3-benzofluorenone (XXVII). If phenol and hydrogen iodide are used for cyclization, the corresponding fluorene is produced.



XXVI

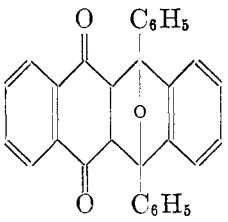


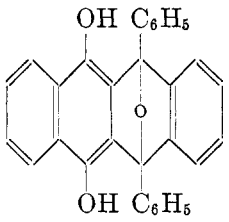
XXVII

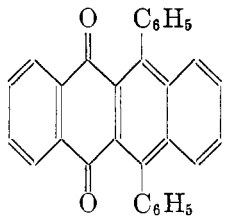
1,4-Diphenyl-2,3-benzofluorenone may be prepared directly by the reaction of 1,3-diphenylisobenzofuran with indene (354). The adduct first formed dehydrates under the conditions of the experiment to give the fluorenone. This appears to be the sole example observed of the rupture of an oxide bridge by heat alone.

Bergmann (83) added 1,4-naphthoquinone to 1,3-diphenylisobenzofuran, and

obtained 9,10-endo-oxo-9,10-diphenyl-9,9a,10,10a-tetrahydro-11,12-naphthacenequinone (XXVIII).

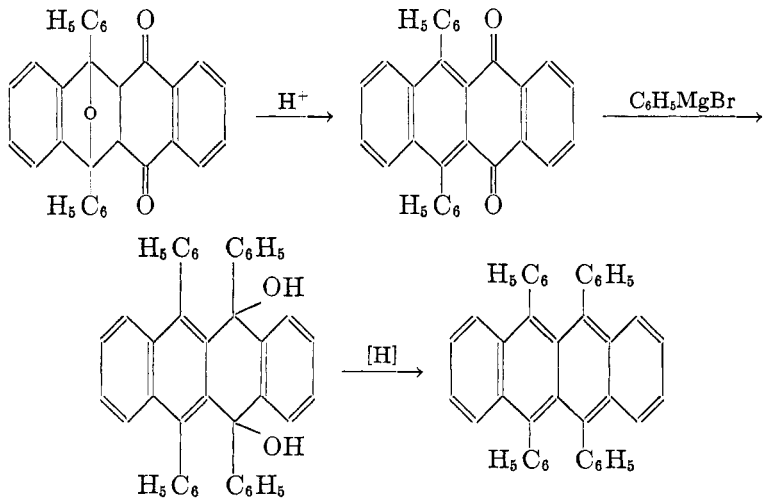

XXVIII


XXIX


XXX

This compound was shown to isomerize when treated with an acetic acid solution of hydrogen bromide; one of the several possible products of isomerization lost 2 moles of water in the process to give 9,10-diphenyl-11,12-naphthacenequinone (XXX), which was isolated from the reaction mixture. The other product isolated from the isomerization reaction was 1,4-diphenyl-1,4-endo-oxo-1,4-dihydro-2,3-benz-9,10-anthraquinol; it may be that the quinol can be converted into XXX by further action of hydrogen bromide.

Dufraisse and Compagnon report (185) the reaction of 1,4-naphthoquinone with 1,3-diphenylisobenzofuran, obtaining the same adduct (XXVIII) as did Bergmann. On treatment with hydrogen chloride or sulfuric acid, they report that the oxide bridge was ruptured and the product obtained by subsequent dehydration was XXX. No mention of XXIX was made. The quinone XXX was made use of in the synthesis of rubrene; XXX was treated with phenylmagnesium bromide in xylene at elevated temperatures, for no reaction occurred at ordinary temperatures. The dihydroxy compound thus obtained was dehydrated and reduced to rubrene using iron and acetic acid:



A number of other isobenzofurans have been studied, but only to a limited extent. 1,3-Bis(α-naphthyl)isobenzofuran (355) adds maleic anhydride and

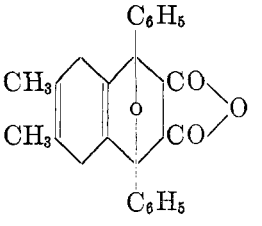
acrolein. The properties of these resulting adducts resemble those of the diphenyl analogs.

1,3-Bis(3,5-dibromo-4-hydroxyphenyl)isobenzofuran (356) adds maleic anhydride or maleic ester in boiling toluene. Hydrogen chloride splits out water and the adducts are thereby aromatized to 1,4-bis(3,5-dibromo-4-hydroxy)-2,3-naphthalic anhydride or ester.

1,3-Bis(*p*-chlorophenyl)isobenzofuran (6) has been reported to add maleic anhydride.

1,3-Diphenyl-5,6-dimethylisobenzofuran (3) adds maleic anhydride. This addition is so readily reversible that purification is difficult. The adduct is stable in the solid state, but is extensively dissociated in solution.

1,3-Diphenyl-5,6-dimethyl-4,7-dihydroisobenzofuran adds maleic anhydride, and the product (XXXI) contains a 1,4-cyclohexadiene ring.

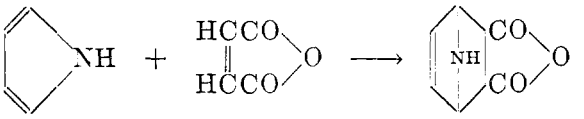


XXXI

D. Pyrroles

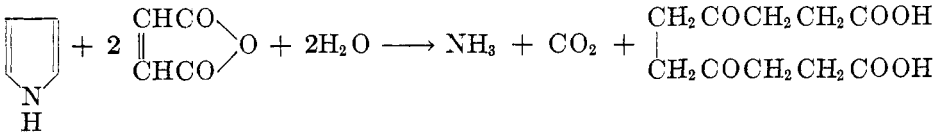
Pyrroles, the heterocyclic nitrogen atom of which occupies a position in the Periodic Table between the corresponding carbon and oxygen atoms of cyclopentadiene and furan, respectively, might be expected to act toward dienophiles as do these other two classes of matter. In no case is this true.

The reaction which would be anticipated is as follows:

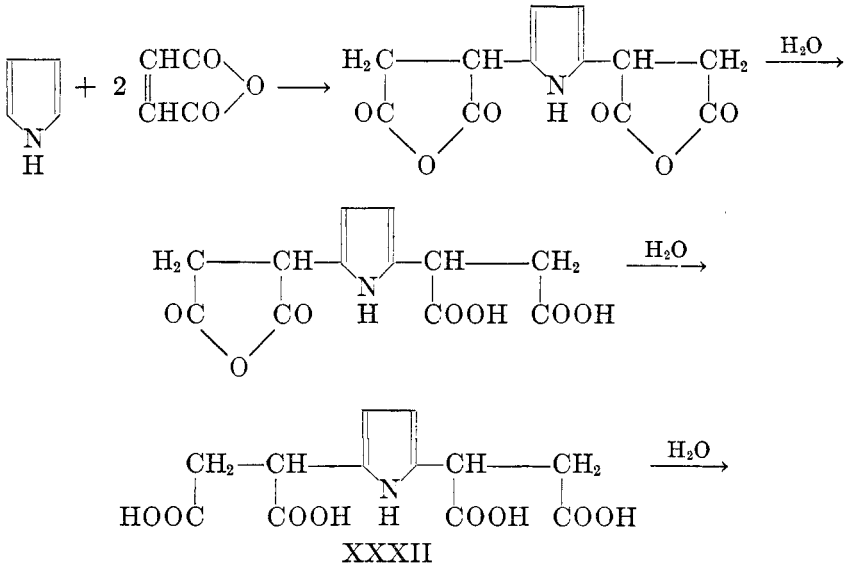


This type of reaction is not observed, and it is always found that heterocyclic dienes which contain nitrogen as a member of the ring show abnormal diene reactions. It is also found that the solvent is an important factor in determining the structure of the main product of the reaction.

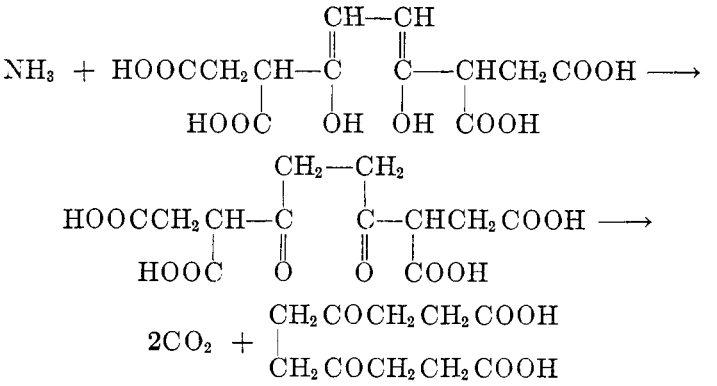
Pyrrole itself shows the following reaction (156) with maleic anhydride in an aqueous medium:



In addition, there is obtained a small amount of 2,5-pyrrolylenedisuccinic acid (XXXII), which lends credence to the following mechanism for the pyrrole reaction:

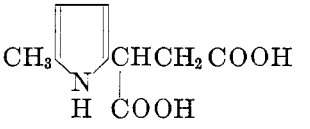


XXXII



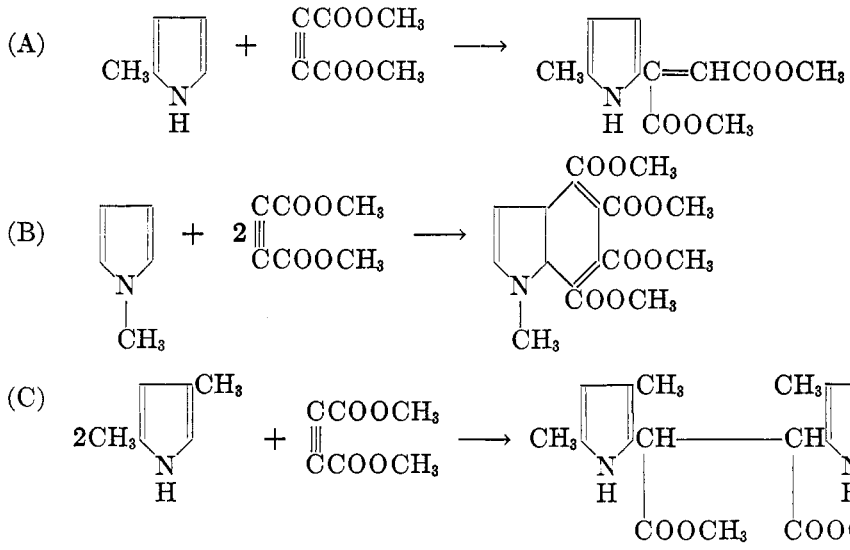
It will be recalled that a somewhat similar reaction is shown by acrolein and furan in the presence of small amounts of sulfur dioxide (page 472).

2-Methylpyrrole reacts somewhat similarly with maleic anhydride in aqueous solution to give 2-methyl-5-pyrrolylsuccinic acid (XXXIII) (156). 1-Methylpyrrole (156) reacts to give the *N*-methyl derivative of XXXII.

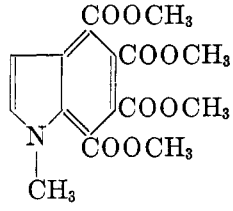


XXXIII

The reactions of pyrroles with acetylenedicarboxylic acid and its esters are also abnormal. In general, they follow one or more of three distinct types:



2,3,4-Trimethylpyrrole (155) reacts with dimethyl acetylenedicarboxylate and also with maleic anhydride according to Type A. As indicated in the type reactions, 2-methylpyrrole reacts according to Type A (154, 155, 156), 1-methylpyrrole follows Type B, and 2,4-dimethylpyrrole follows Type C. But when the dienophile is acetylenedicarboxylic acid instead of its dimethyl ester, 1-methylpyrrole follows Type A (155). The ester resulting from the Type B reaction of 1-methylpyrrole may be oxidized with bromine (155) to give XXXIV, which may be saponified and decarboxylated to give *N*-methylindole in high yield.



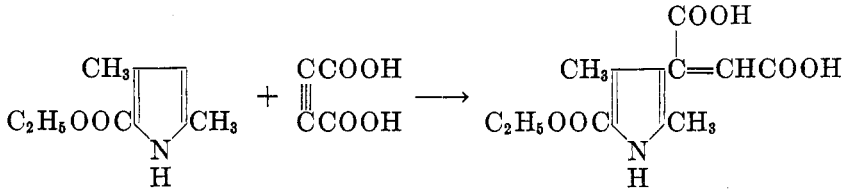
XXXIV

Ethyl 2,4-dimethylpyrrole-5-carboxylate reacts with acetylenedicarboxylic acid to give a product differing in type from all adducts discussed previously (225).

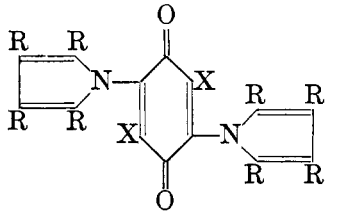
It may be seen that all α-positions are blocked and that substitution can occur only on the lone β-position. One might surmise that substitution occurs preferentially on the α-positions, but can occur on the β-positions if the former are blocked.

2,5-Dimethylpyrrole, 2,3,4-trimethylpyrrole, and 2,4-dimethyl-3-ethyl-

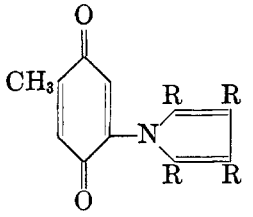
pyrrole react with *p*-benzoquinone and also with 2,5-dibromo-*p*-benzoquinone (305) to give adducts of the general formula XXXV, where R is hydrogen or an alkyl group, and X is hydrogen or bromine. The by-product of the reaction is the corresponding quinhydrone or hydroquinone.



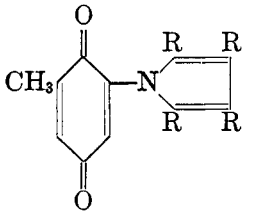
A similar reaction is shown with *p*-toluquinone (305), but only 1 mole of the pyrrole is involved. The structure of the product is not certain, being either XXXVI or XXXVII; the former is to be preferred tentatively. The inhibiting



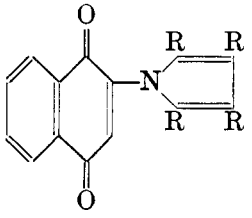
XXXV



XXXVI



XXXVII

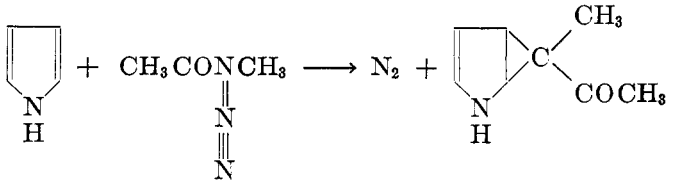


XXXVIII

effect of substituents in the *p*-benzoquinone ring appears to be carried over into these abnormal diene syntheses; it is to be noted that easily removed substituents (such as bromine) do not hinder addition in these reactions.

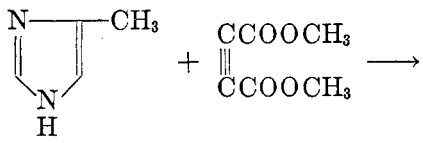
Addition of the above pyrroles also occurs to 1,4-naphthoquinone, giving XXXVIII.

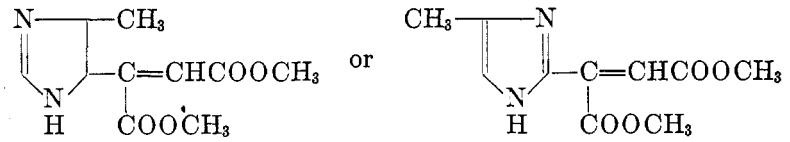
Azibutanone (163) reacts with pyrrole to eliminate nitrogen and to form 2,3-dihydro-2,3-(1-acetyl)ethylidenepyrrole:



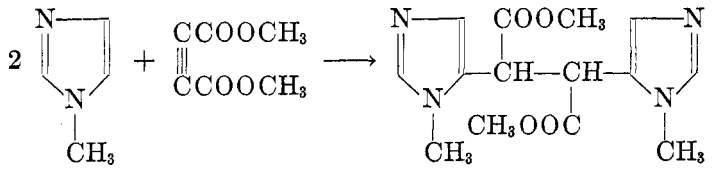
E. Imidazoles

Imidazoles react with acetylenedicarboxylic esters in a manner similar to that of the pyrroles. Thus 4-methylimidazole reacts according to Type A to give one of the two possible isomers (155); it is not certain which isomer is produced.

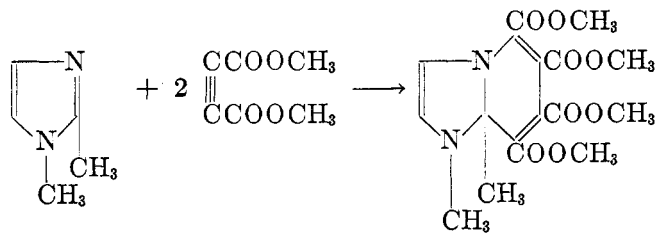




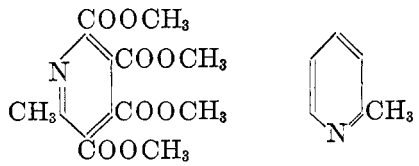
1-Methylimidazole reacts (155) according to Type C:



1,2-Dimethylimidazole reacts (155) according to Type B:



Bromine treatment of the product from 1,2-dimethylimidazole gives XXXIX, which may be saponified and decarboxylated to α-picoline (XL).

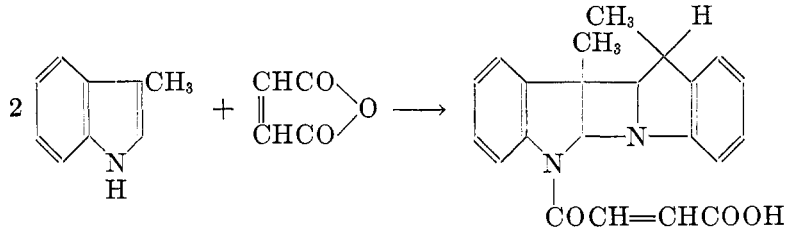


XXXIX XL

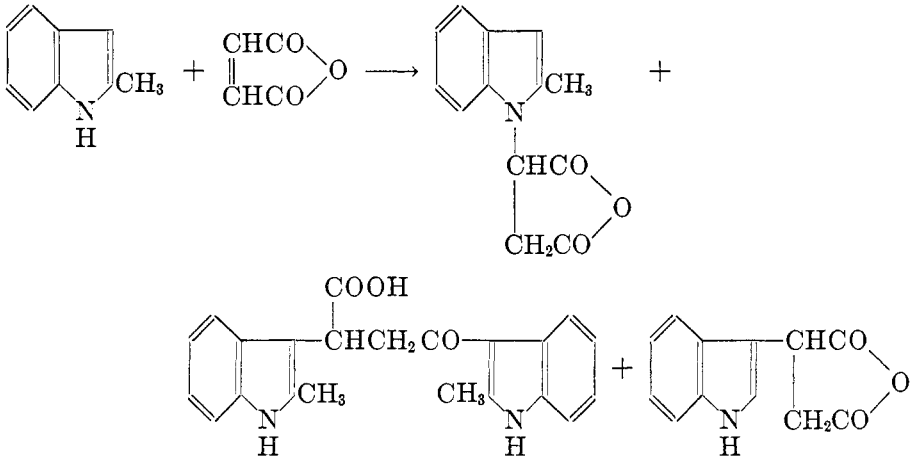
F. Indoles and carbazole

Carbazole is the dibenzolog of pyrrole; it does not react with maleic anhydride. A method of separation of anthracene from carbazole in the coal-tar anthracene fraction is based on this fact (303).

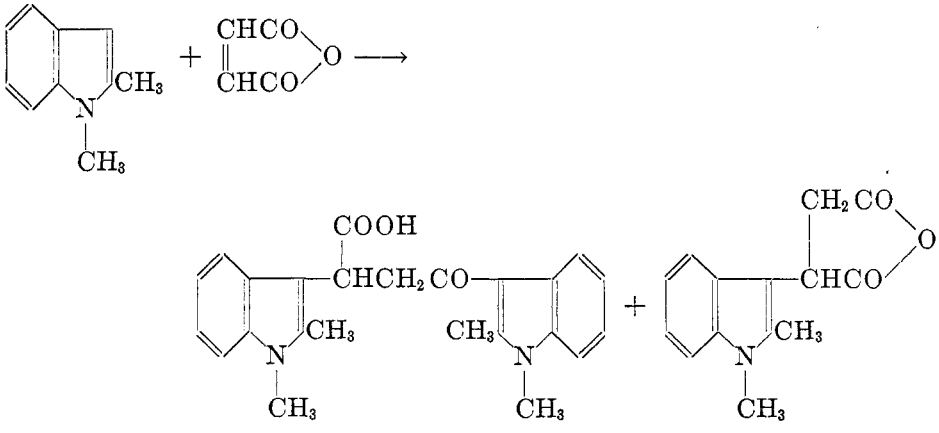
Indoles, the monobenzologs of pyrroles, react with maleic anhydride, acetylenedicarboxylic esters, and *p*-benzoquinone (143) in highly abnormal manners. For example, skatole reacts with maleic anhydride as follows:



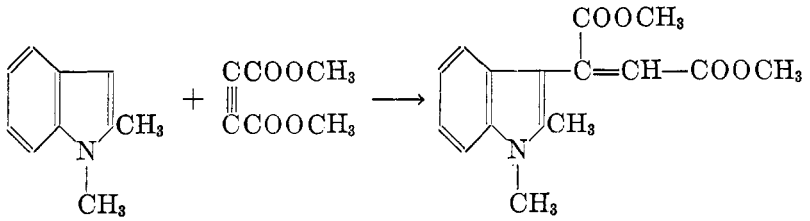
Indole reacts in a manner identical with skatole, but α-methylindole reacts in a most original manner to give three products:



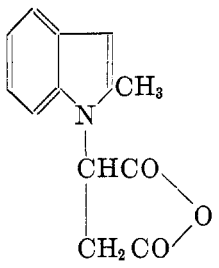
1,2-Dimethylindole reacts in a manner similar to α-methylindole, but does not form the *N*-substituted type of compound.



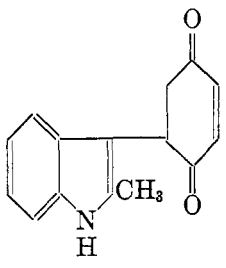
It reacts somewhat similarly with the dimethyl ester of acetylenedicarboxylic acid.



2-Methylindole (143, 294) reacts with maleic anhydride to give products analogous to those from 1,2-dimethylindole and, in addition, forms a third compound (XLI). Reaction with *p*-benzoquinone gives XLII, which is analogous to one of the maleic anhydride products.



XLI



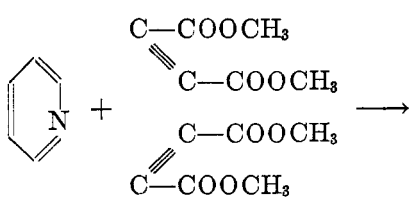
XLII

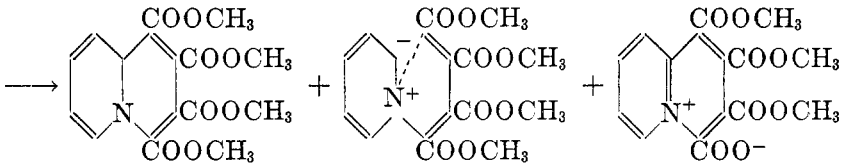
Unlike the pyrroles, azibutanone is without action on indole, skatole, and 2-methylindole (163).

G. Pyridine, its derivatives, and its benzologs

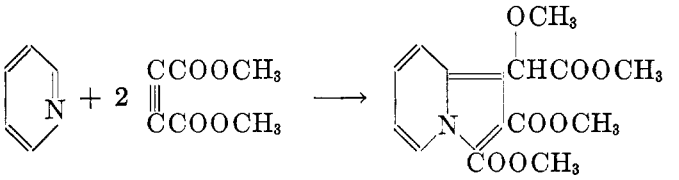
The reactions of pyridine as a diene may be regarded, on initial consideration, as being those of the alternating double bonds of the Kekulé structure. However, the reaction products of this as well as of the other nitrogenous heterocycles are not those anticipated from a consideration of the simple diene–dienophile reaction. The nature of the products isolated may, however, offer a clue as to the mechanism of diene reactions in general.

The reaction products of pyridine and acetylenedicarboxylic dimethyl ester differ according to the nature of the solvent employed. In acetic acid solution, the sole reaction observed is trimerization of the ester to give hexamethyl mellitate (135, 142, 160); apparently the trimerization is catalyzed by pyridinium ion. In ether solution, an entirely different reaction occurs with formation of condensed ring systems containing nitrogen as one of the bridge atoms (140, 141, 164):



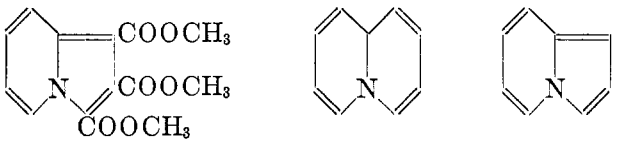


In methanol solution at 0°C., the product differs from that obtained in ether (164).



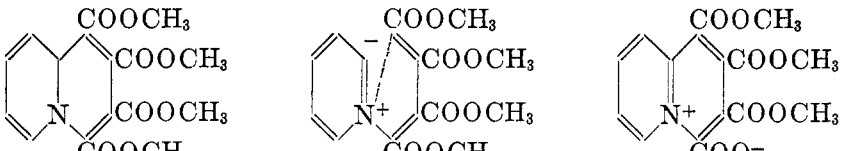
At higher temperatures, or by treatment of the above product with bromine in methanol solution, there is also obtained trimethyl indolizintricarboxylate (XLIII).

In the interests of nomenclature, it must be stated that the parent compounds XLIV and XLV are named quinizolin and indolizin, respectively. In the



XLIII XLIV XLV

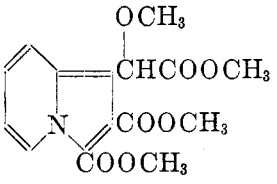
literature of Diels and Alder, tetramethyl quinizolin-1,2,3,4-tetracarboxylate (XLVI) is referred to as "the yellow substance", the carbide-type of intermediate (XLVII) is referred to as "the red substance", and the zwitter ion (XLVIII) is named "Kashimoto's Compound". The chemistry of these substances has been



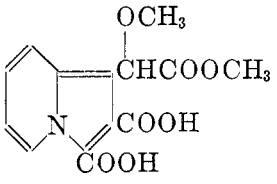
XLVI XLVII XLVIII

investigated extensively by Diels and his collaborators. The proof of the structure of XLVI is based mainly on oxidative degradation (140, 142) to α-picolinic acid *N*-oxide. Successive action of bromine or nitric acid and pyridine on XLVI gives rise to Kashimoto's compound (XLVIII). Other typical reaction sequences include the degradation of XLVI to norlupine (142), the degradation of XLIII to octahydroindolizin (164), and the degradation of XLVI to an isomer of norlupinane (171).

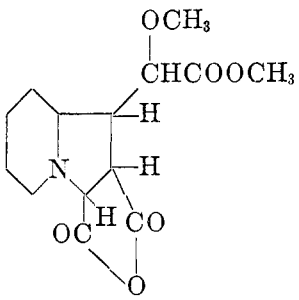
Adduct XLIX, from pyridine and acetylenedicarboxylic dimethyl ester in methanol solution at 0°C., may be reduced catalytically to a tetrahydro compound. It is attacked by acetic anhydride, suffering replacement of a



XLIX

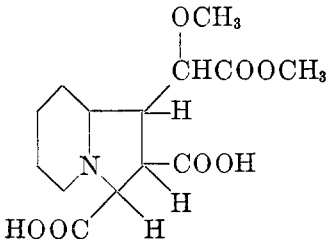


L

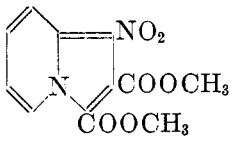


LI

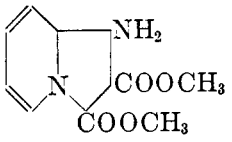
—$COOCH_3$ group by an acetyl group (164). XLIX is saponifiable to a dicarboxylic acid (L), hydrogenation of which followed by dehydration with acetic acid yields an anhydride (LI). If hydrogenation precedes saponification, the final product is the acid (LII), which does not form an anhydride because the two carboxyl groups are *trans* to each other (164).



LII

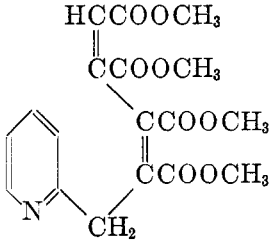


LIII

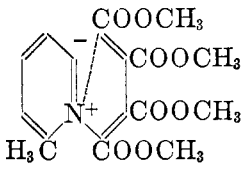


LIV

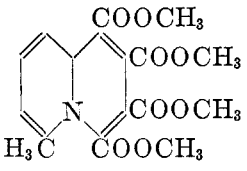
The —$CH(OCH_3)COOCH_3$ side chain of XLIX is readily removed by action of an acetic acid solution of nitric acid to give LIII, which can be easily reduced to give LIV.



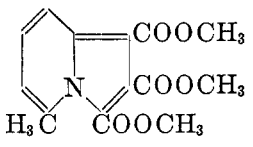
LV



LVI



LVII

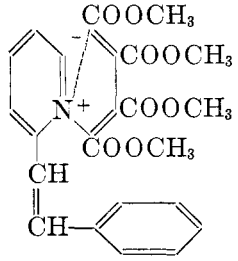


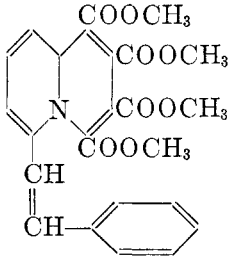
LVIII

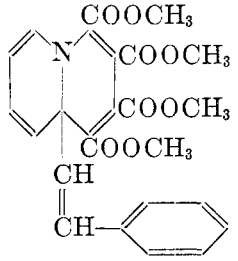
α-Picoline reacts with acetylenedicarboxylic dimethyl ester in ether solution at 0°C. to give a red, stable adduct of formula LV. There is also produced a

yellow, labile, carbide-type of intermediate (LVI), which is stabilized by heat or by acetic acid to give the orange compound (LVII). Oxidation of LVII with sodium dichromate in acetic acid gives an indolizin compound (LVIII), further oxidation of which gives 6-methyl-2-picolinic acid *N*-oxide (167).

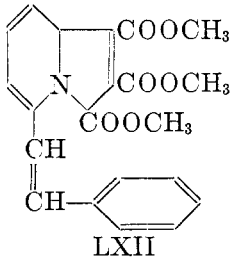
The reaction of 2-stilbazole (165) with acetylenedicarboxylic dimethyl ester in ether solution proceeds to give an orange labile compound (LIX), which is converted by heat into the first stable addition product (LX). Further heating produces the second stable addition product (LXI), which is unique in its possession of an angular group. Unlike the labile orange product (LIX) or the first stable addition product (LX), LXI does not seem to be convertible into the

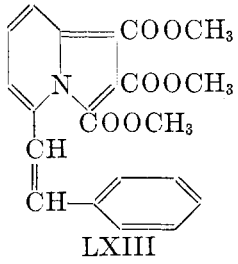

LIX


LX

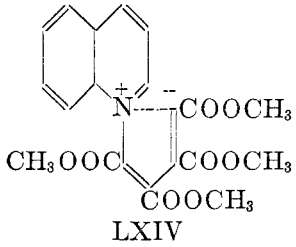

LXI

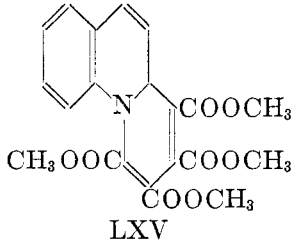
indolizin type of compound (LXII) by boiling in acetic acid, nor does it seem to be convertible into LXIII by sodium dichromate in acetic acid.

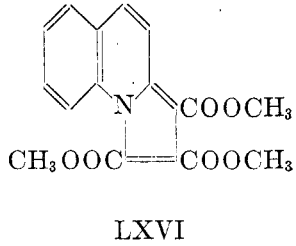

LXII


LXIII

Quinoline (141, 155) reacts with acetylenedicarboxylic dimethyl ester in ether solution much as does pyridine, for it forms a yellow labile product (LXIV), which is transformed by heat into red tetramethyl 5,6-benzquinizolin-1,2,3,4-tetracarboxylate (LXV). Like the corresponding quinzolin derivative, LXV is easily oxidized by chromic or dilute nitric acid to the indolizin derivative (LXVI).

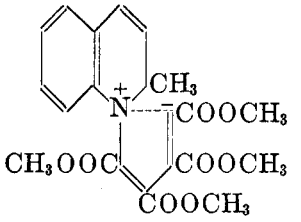

LXIV


LXV

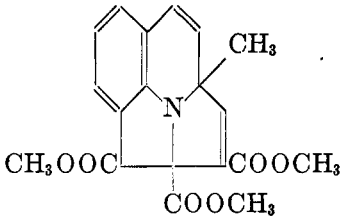

LXVI

α-Quinaldine (155) reacts with an ether solution of dimethyl acetylenedicarboxylate to give a labile compound of anticipated formula (LXVII). It is

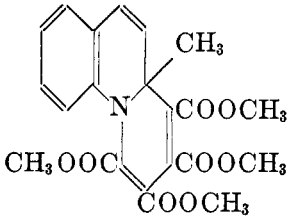
heat-stabilized to give a compound first thought to be LXIX, but this was shown to be erroneous, for the compound was LXVIII. During the heat stabilization LXX is also formed through condensation with the reactive methyl group, followed by rearrangement.



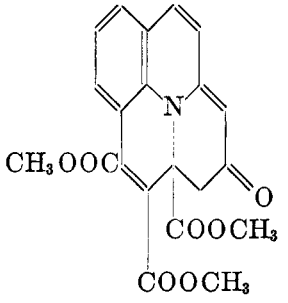
LXVII



LXVIII



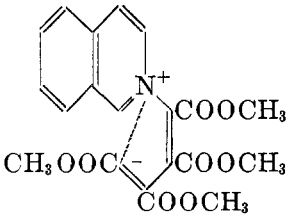
LXIX



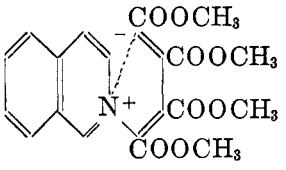
LXX

2-Styrylquinoline (86) appears to form only the maleate on treatment with acetylenedicarboxylic dimethyl ester.

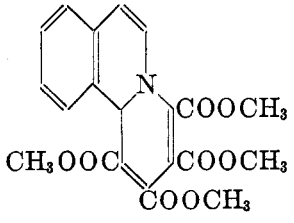
Isoquinoline (155, 159) reacts with acetylenedicarboxylic dimethyl ester in ether solution to give, mainly, an orange-yellow labile adduct to which structure LXXI has been assigned. A small amount of a red isomer is also produced, to which structure LXXII has been assigned. LXXII is heat-stabilized to LXXIII, while LXXI is heat-stabilized to a mixture of LXXIII and LXXIV.



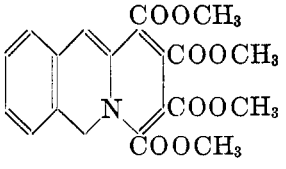
LXXI



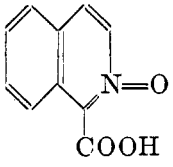
LXXII



LXXIII



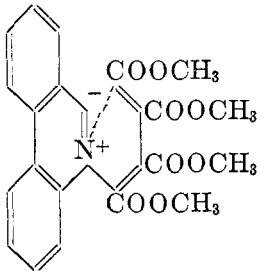
LXXIV



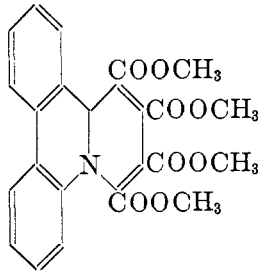
LXXV

The compound LXXIII, like its pyridine and quinoline analogs, can be degraded oxidatively to LXXV.

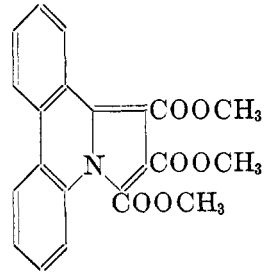
9-Phenanthridine (174) acts much in the same manner as pyridine and quinoline when treated with acetylenedicarboxylic dimethyl ester. The first product is a labile adduct (LXXVI); the stable adduct (LXXVII) is obtained



LXXVI

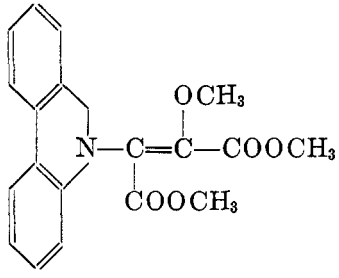


LXXVII

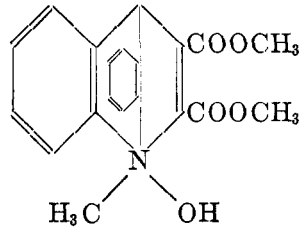


LXXVIII

by boiling LXXVI first with quinoline and then with ethyl alcohol. Crystallization of LXXVI from ether or acetonitrile gives the indolizin compound (LXXVIII). Crystallization from methanol gives LXXIX.



LXXIX

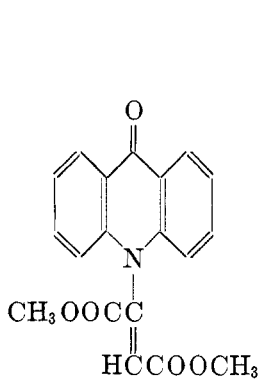


LXXX

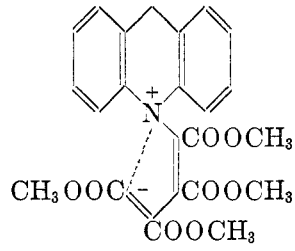
Acridine was treated with maleic anhydride by Barnett (72), who failed to obtain an adduct. Diels and his students (173) obtained various products with acridine and acetylenedicarboxylic dimethyl ester. Refluxing the two reactants in methanol for two days gives the bridged quaternary hydroxide (LXXX); in addition, 1 to 2 per cent of a light yellow compound (LXXXI) is also formed. Ethanol forms the bridged ethylacridonium hydroxide corresponding to LXXX. When dioxane is the solvent, 20 to 30 per cent of the product is LXXXI, which probably results by atmospheric oxidation on evaporation of the solvent. The remainder of the dioxane product is the ruby-red labile adduct (LXXXII).

In ether solution, the product is mainly the *trans*-isomer of LXXXI, although some of the *cis*-isomer is formed. The yield of LXXXII is very small in this case. If perhydrol is incorporated into the reaction mixture which employs methanol as the solvent, a nearly quantitative yield of the *cis*-form of LXXXI results. Atmospheric oxidation of LXXX also results in formation of the *cis*-form of LXXXI. Crystallization of the *trans*-isomer of LXXXI from pyridine gives the *cis*-isomer, and oxidation of the ruby-red labile adduct

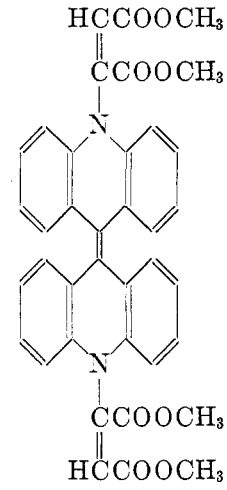
(LXXXII) with perhydrol gives a 90 per cent yield of the *cis*-form of LXXXI plus small amounts of LXXXIII.



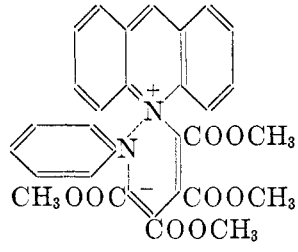
LXXXI



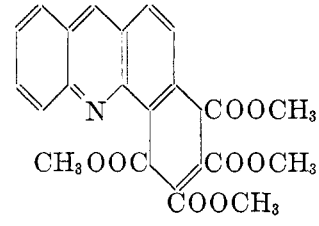
LXXXII



LXXXIII



LXXXIV



LXXXV

Pyridine forms a complex with LXXXII, to which structure LXXXIV has been given.

An abnormal stable adduct, LXXXV, is formed by dissolving LXXXII in concentrated sulfuric acid, followed by dilution with water.

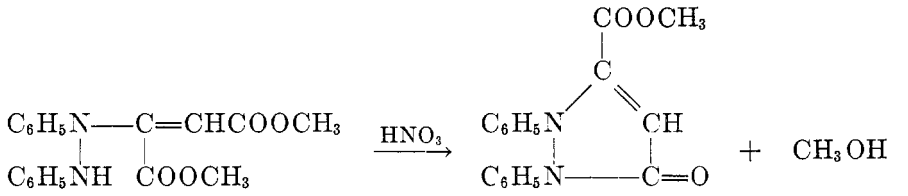
XIV. MISCELLANEOUS NITROGEN COMPOUNDS

The miscellaneous nitrogen compounds to be discussed under this heading are not dienic, but were studied in connection with the heterocyclic nitrogen-containing dienes. Their reactions are quite similar to those of the pyrroles and pyridines.

A. Hydrazines

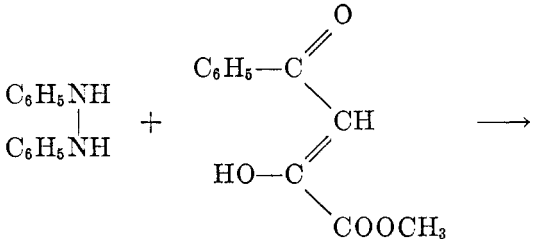
A few hydrazines were studied by Diels and his coworkers; the first to be considered is *sym*-diphenylhydrazine (hydrazobenzene). It reacts with acetylenedicarboxylic dimethyl ester (168) in methanol solution:

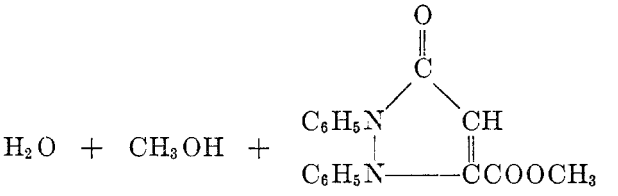
Nitric acid acts upon the adduct:



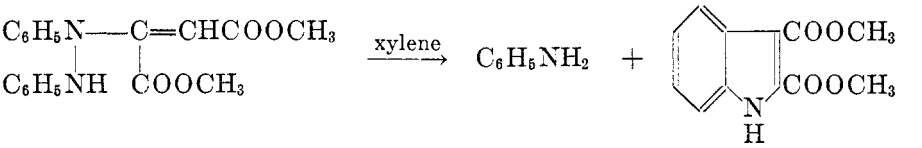
If the formation of the adduct is conducted in acetic acid solution instead of methanol, the second compound (produced above by means of nitric acid) is formed directly.

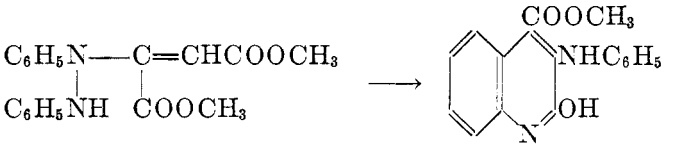
The tautomeric form of oxalacetic ester reacts with hydrazobenzene directly to give the same compound:





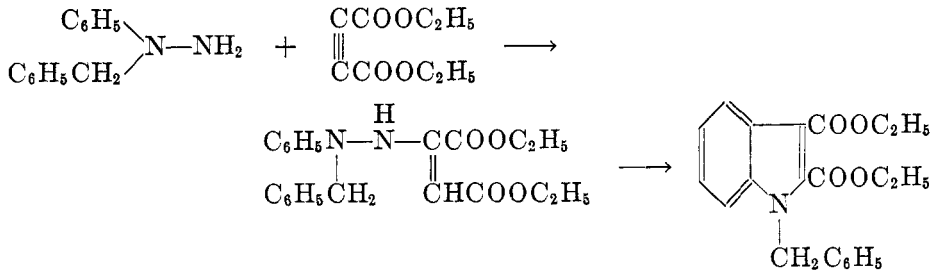
The adducts undergo a number of reactions, two of the most important being the conversions to indole and quinoline derivatives. Heating in xylene yields indole derivatives, while heat alone or heating in pyridine or dimethylaniline yields quinoline derivatives:



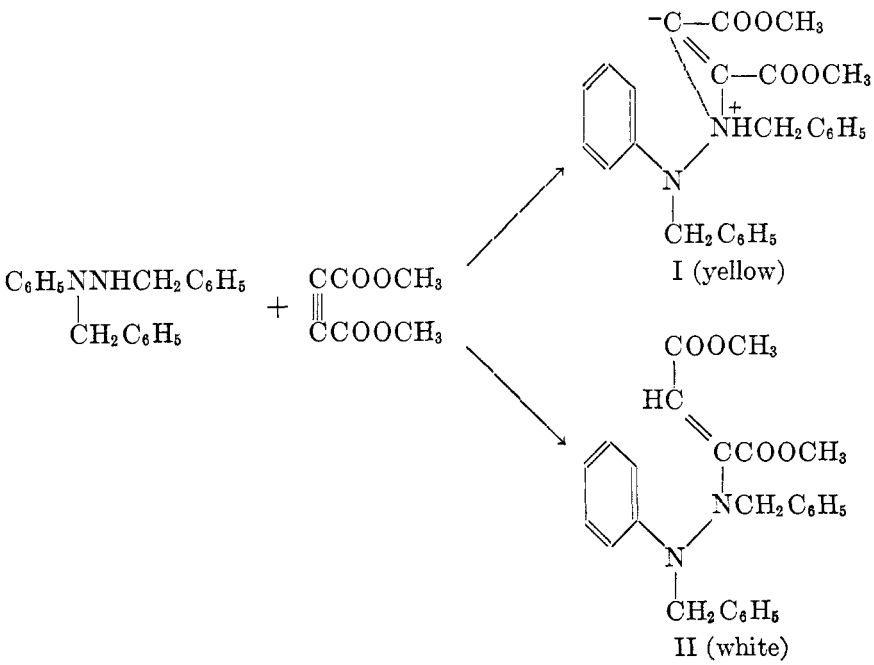


In methanol solution, *p*,*p*′-hydrazotoluene and *N*-phenyl-*N*′-benzylhydrazine (169) give compounds corresponding to that from hydrazobenzene and acetylenedicarboxylic dimethyl ester in methanol solution. Analogous compounds are also formed by *sym*-dibenzylhydrazine and tribenzylhydrazine.

Unsymmetrical benzylphenylhydrazine also gives an analogous adduct in cold methanol; the adduct is, however, more labile than the adducts from hydrazines with one or two substituents on each nitrogen atom. In hot water, the adduct forms the indole type with loss of ammonia:

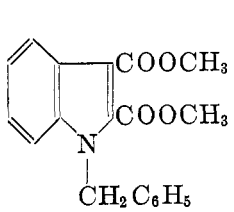


1-Phenyl-1,2-dibenzylhydrazine resembles both pyridine and the above hydrazines in its reaction with acetylenedicarboxylic dimethyl ester, giving a mixture of I and II.

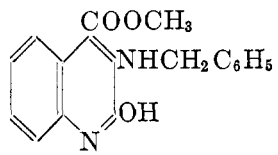


I (yellow)

II (white)



III

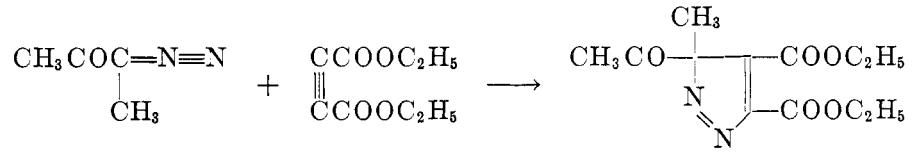


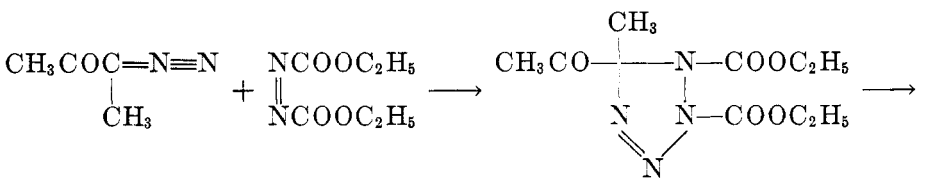
IV

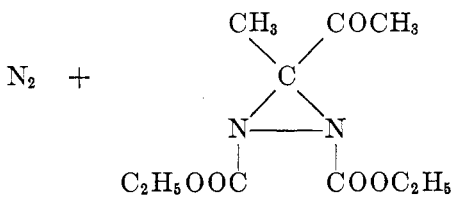
Both I and II give indole and quinoline types. When boiled in xylene, they both give III; when boiled in pyridine, they both give IV.

B. Azibutanone

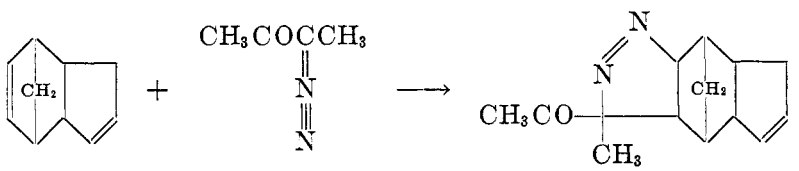
The reactions of azibutanone, $CH_3COC(CH_3)=N\equiv N$, with pyrroles have been discussed earlier. While it reacts with this class of compounds, it does not react with its benzologs, such as indole and skatole. It also shows no reaction with allphatic dienes or monomeric cyclopentadiene. It reacts violently with acetylenedicarboxylic ester and with azodicarboxylic ester:



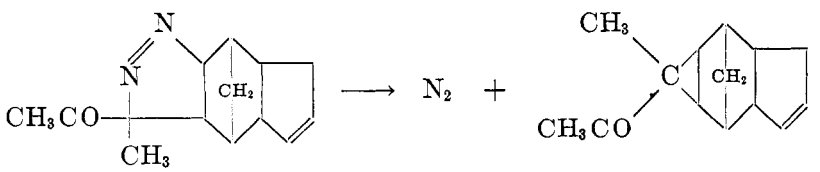




Azibutanone also reacts with the highly active double bond of the bicycloheptene derivatives; for example, the reaction with cyclopentadiene dimer is as follows:



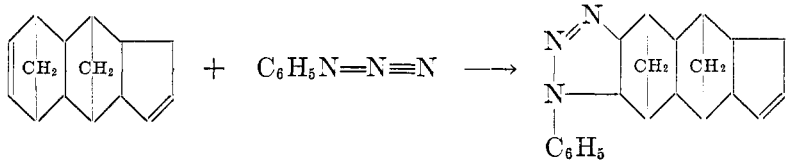
The adduct loses nitrogen on vacuum distillation:



C. Phenyl azide

Phenyl azide reacts with the double bond of bicycloheptene derivatives; indeed, the reaction is almost specific for this ring system and was much used by

Alder and Stein in the proof of structure of the polymers of cyclopentadiene. With the trimer of cyclopentadiene, for example, it reacts as follows:

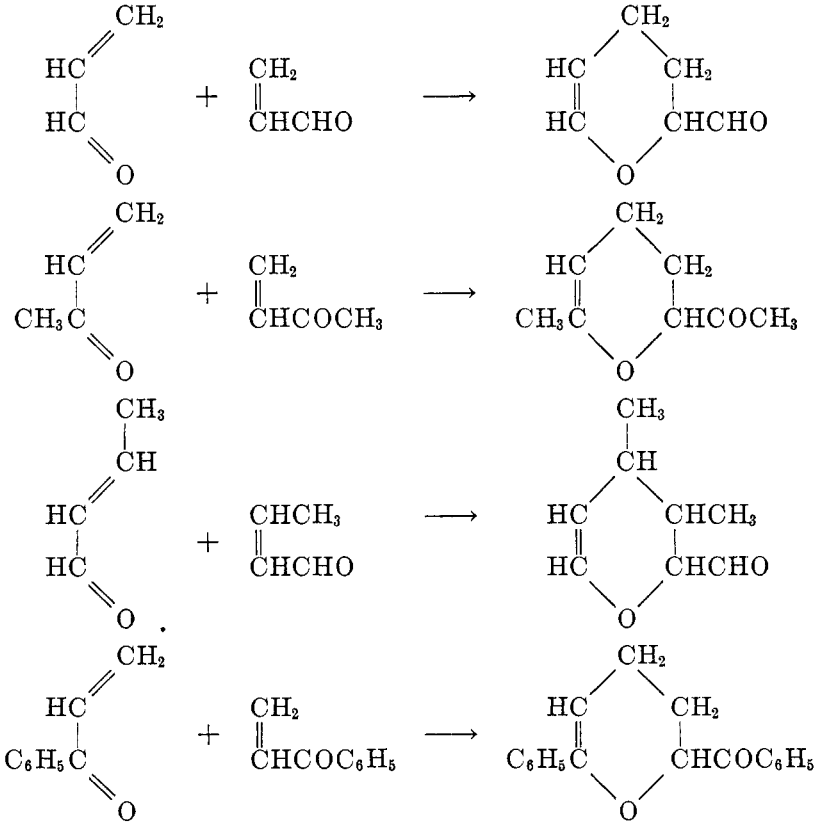


XV. MISCELLANEOUS DIENE SYNTHESES

A. Dimerizations of carbonylenic dienophiles

Alder and his coworkers have recently (380, 381, 383) published a series of papers on the dimerizations of α,β-unsaturated aldehydes and ketones. Diene syntheses of this type are unique in that the function of the diene is played by the grouping C=C—C=O instead of C=C—C=C.

This type of diene synthesis may be illustrated by the dimerizations of acrolein (383), methyl vinyl ketone (380), crotonaldehyde (381), and acrylophenone (381). The structures of the dimers of acrolein and of methyl vinyl ketone have been proved, while the structures of the dimers of the other two ketones have not been elucidated conclusively as yet. The reactions involved are the following:

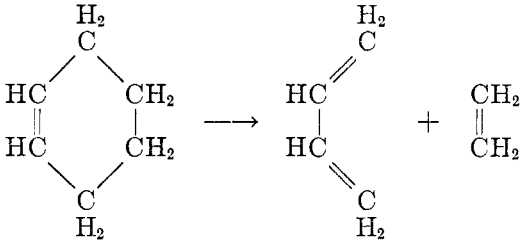


Addition occurs in a manner so that the RCO— group of the dimer is always ortho to the ring oxygen atom, and never meta (381) (for a novel example, see reference 416).

B. Reverse diene syntheses[3]

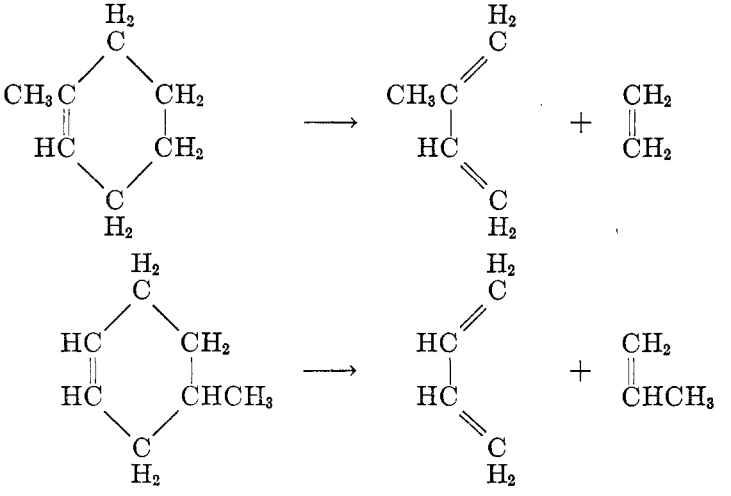
There are a number of compounds which, when heated strongly, decompose into a diene and an olefinic compound, although the diene and olefin have not been observed to recombine to give the original compound. For want of a better term, these are called reverse diene syntheses.

Perhaps the best known of these reverse diene syntheses is the Kistiakowsky (414) hot-wire method of producing butadiene from cyclohexene:

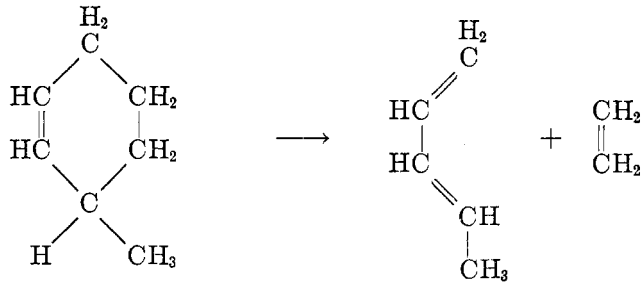


The advantage of the hot-wire method over other pyrolytic methods is that cracking is accomplished without use of an inert gas and without formation of polymeric material. If the pyrolysis is conducted by use of a hot tube, the butadiene, cyclohexene, and ethylene interact and considerable quantities of polymeric materials are obtained. This interaction may be largely avoided by diluting the charged cyclohexene with an inert gas, which is usually steam (392, 427).

Homologs of cyclohexene have likewise been subjected to pyrolysis to give a diene and an olefin. These pyrolyses were conducted using a hot tube and a



[3] Suggested by Dr. A. O. Rogers. Subsequently, Butz (411) has reversed the decomposition of cyclohexane to butadiene and ethylene.



diluting gas. Compounds thus studied are 1-methyl-1-cyclohexene (392, 427), which yields isoprene and ethylene, 4-methyl-1-cyclohexene (427), which yields butadiene and propylene; and 3-methyl-1-cyclohexene (392), which yields ethylene and piperylene.

There are certain other examples known of reverse diene syntheses, but these cannot be reviewed because of current patent situations.

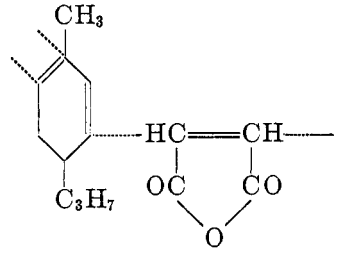
XVI. MECHANISM AND STEREOCHEMISTRY OF THE DIENE SYNTHESIS

A. Postulate of mechanism

This section will deal with the theory of addition and the stereochemical effects observed in the diene synthesis.

Little appears to be known concerning the electronic changes and intermediates formed in the diene synthesis. The transient yellow color observed during the addition of maleic anhydride to a diene and similar transient colors observed in other diene syntheses almost certainly indicate that reactive intermediates, possibly free radicals, are involved in the reaction. A suggestion as to the constitution of these intermediates may be obtained from the proposed structures of the labile adducts obtained by addition of acetylenedicarboxylic ester to heterocycles derived from pyridine. These carbide-type intermediates are highly colored; the stable adducts formed from them by suitable treatment are less intensely colored.

Littmann (131) suggests a mechanism for the diene synthesis, which is based on the appearance of the transient yellow color in the α-phellandrene–maleic anhydride reaction and also on the preparation of a polymer of α-phellandrene and maleic anhydride. An intermediate of the type



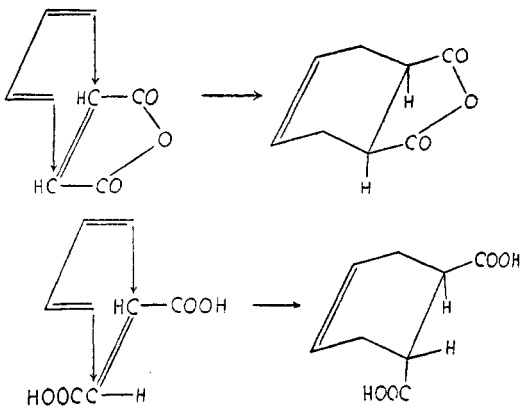
is suggested, wherein there is an alternation of terpene and maleic anhydride molecules. The significance of the dotted lines is not absolutely clear; possibly they indicate a type of coördinate linkage.

B. The cis principle

The stereochemical aspects of the diene synthesis have been investigated intensively by Alder and his students. It is a most noteworthy fact that the diene synthesis is highly stereoselective. When several stereoisomers of an adduct are theoretically possible, only one or perhaps two of these isomers are actually formed. These stereochemical phenomena have been discussed and explained in great detail by Alder and Stein in their treatise (27), which will be reviewed at this point. The three-dimensional sketches which appear in the next portions of this review are adaptations from that treatise.

The various stereochemical phenomena attendant on the diene synthesis may be grouped under three main headings. The first of these is the "*cis* principle", which is applicable to all diene syntheses. This principle states that in the diene synthesis, addition of a diene to the dienophilic double bond is invariably a pure *cis*-addition. Accordingly, butadiene and maleic acid give *cis*-1,2,3,6-tetrahydrophthalic acid, and butadiene and fumaric acid give *trans*-1,2,3,6-tetrahydrophthalic acid. A *cis*-dienophile will not give rise to a *trans*-adduct, nor will a *trans*-dienophile give rise to a *cis*-adduct. Fumaric ester will not give *cis*-1,2,3,6-tetrahydrophthalic ester with butadiene. The statement should be qualified to the extent that the *cis*-adduct first formed may isomerize to the *trans*-adduct under the conditions of the experiment, particularly if high temperatures are required to effect addition. Thus while the product actually isolated may apparently be the result of *trans*-addition of the diene to the dienophile, it is postulated that the adduct resulting from *cis*-addition is first formed and that this may isomerize to the product actually isolated.

The cases of butadiene with fumaric and maleic acids are graphically illustrated below:

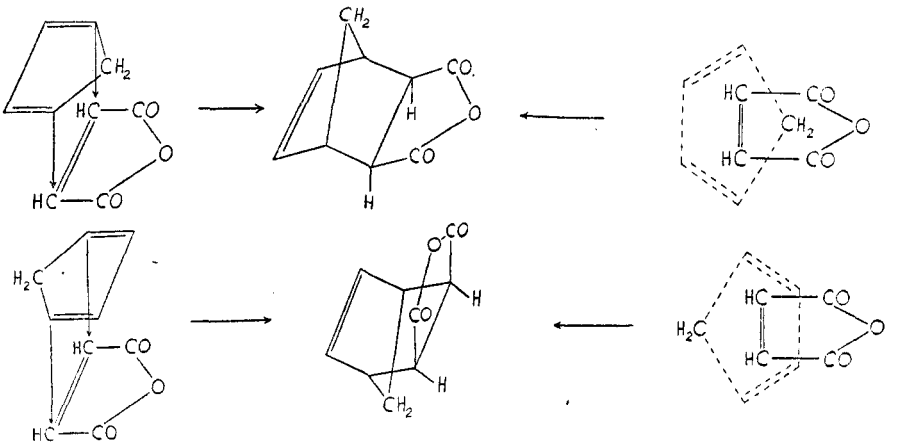


Exclusive of diene addition reactions, there are only a few isolated examples of pure *cis*-additions known. The lecture-hall example is the hydroxylation of double bonds by permanganate. This is practically the sole case of exclusive *cis*-addition known, save for some hydrogenations and the diene synthesis. The hydroxylation by permanganate is illustrated by the formation of meso-

tartaric acid from maleic acid and the formation of racemic tartaric acid from fumaric acid.

C. The general orientation scheme

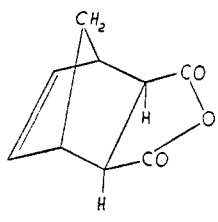
The second heading under which the stereochemical phenomena of diene syntheses may be grouped is termed "the general orientation scheme" by Alder and Stein. The question arising under this heading is whether the diene adds *cis* on one side or the other of the dienophilic double bond. Regardless of which mode of addition actually occurs, the product would be the same if the diene were butadiene, but two isomers are possible with a cyclic diene such as cyclopentadiene. This is illustrated in the two pairs of drawings below. The first pair of drawings represents a side view of the two possible orientations of the reactants. The second pair represents a top view of the two possible orientations, the cyclopentadiene molecule being above the maleic anhydride molecule:



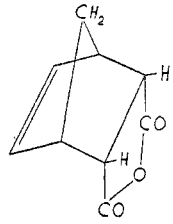
The mode of addition represented by the drawings in which the —CH_2— group of the cyclopentadiene molecule is on the same side of the dienophile molecule as are its carboxylic acid groups gives rise to an acid (I) in which the —CH_2— and carboxyl groups are also on the same side of the molecule. The other two drawings represent a mode of addition wherein the carboxyl and —CH_2— groups are on opposite sides of the double bond of the dienophile; this mode of addition gives rise to an acid (II) in which the endomethylene group is on the opposite side of the molecule from the carboxyl groups. This type of configuration is known as the endo-configuration, whereas the type of configuration possessed by anhydride I is known as the exo-configuration; the prefix "endo" as applied to the —CH_2— bridge should not be confused with the same prefix as applied to the mutual configurations of the carbonyl groups and the bridge itself.

Only one anhydride is formed on the addition of cyclopentadiene to maleic anhydride; this is anhydride II, which is endo-*cis*-1,2,3,6-tetrahydro-3,6-endomethylenephthalic anhydride. Anhydride I, which is not formed in that reaction, is exo-*cis*-1,2,3,6-tetrahydro-3,6-endomethylenephthalic anhydride.

This mode of addition is entirely general; the activating groups which had belonged to the dienophile are always found opposite the endomethylene group with respect to the plane of the six-membered ring (for convenience in discussion, the cyclohexene ring is assumed to be planar). The mode of addition of cyclopentadiene to dienophiles in the absence of complicating factors to be discussed later is exclusively by a mechanism leading to the endo-configuration.

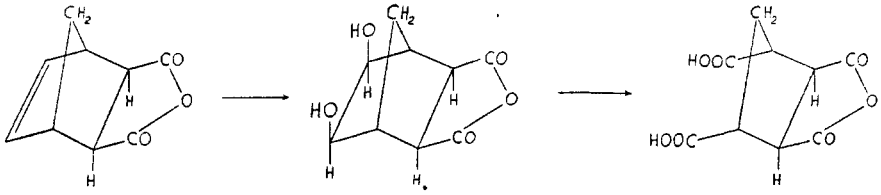


I

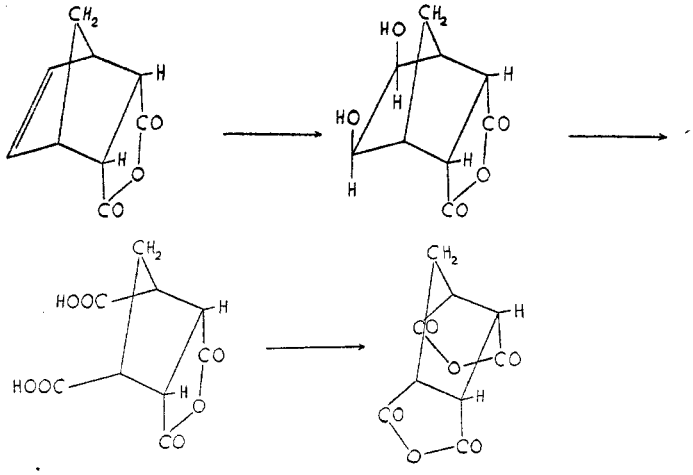


II

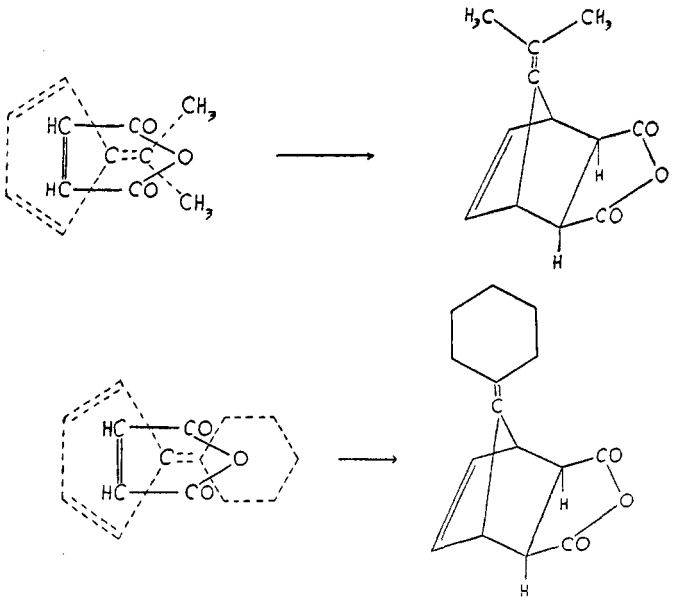
Alder and Stein give a number of proofs of the endo-configuration for the maleic anhydride adduct. One of these rests upon oxidation of the double bond of the adduct. The endo-*cis* adduct was oxidized to the glycol by dilute permanganate; it in turn was oxidized to a cyclopentanetetracarboxylic acid. This acid was found to form a dianhydride. Isomerization of the endo-*cis* acid gave the exo-*cis* isomer. Oxidation of this by the identical procedure used for the endo-*cis* acid eventually yielded a cyclopentanetetracarboxylic acid which formed a monoanhydride, but not a dianhydride:



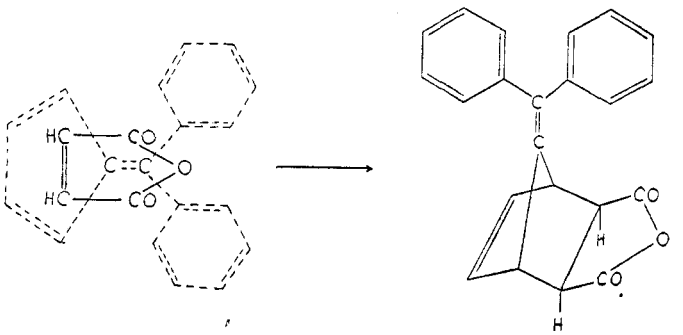
I



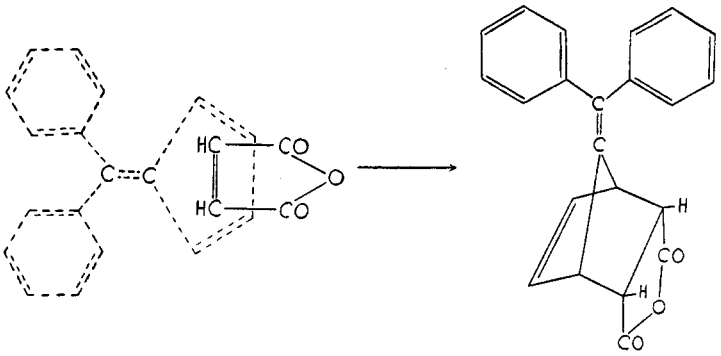
In spite of the fact that cyclopentadiene, cyclohexadiene, and similarly constituted dienes add to give adducts possessing the endo-configuration, it is well not to generalize by stating that all dienes add dienophiles to give adducts possessing the endo-configuration. A better generalization is that dienes add to dienophiles according to an orientation of their molecules which permits maximum accumulation of double bonds just prior to consummation of addition. This statement would include not only the reacting double bonds of the diene and dienophile, but also the double bonds of the carboxyl group and other double bonds of similar character and function. With fulvenes, it also includes the double bond of the $C{=}CR_2$ group and double bonds as they may occur in R. In fact, the double bonds of dimethyl- and pentamethylene-fulvenes are so distributed that maximum accumulation of double bonds is slightly in favor of an orientation leading to the formation of the exo-adduct (the adduct is 60 per cent exo-isomer):



With diphenylfulvene, the double bonds of the phenyl groups are also a determining factor in the orientation of the adduct. In this case, the product is exclusively of the exo-configuration:



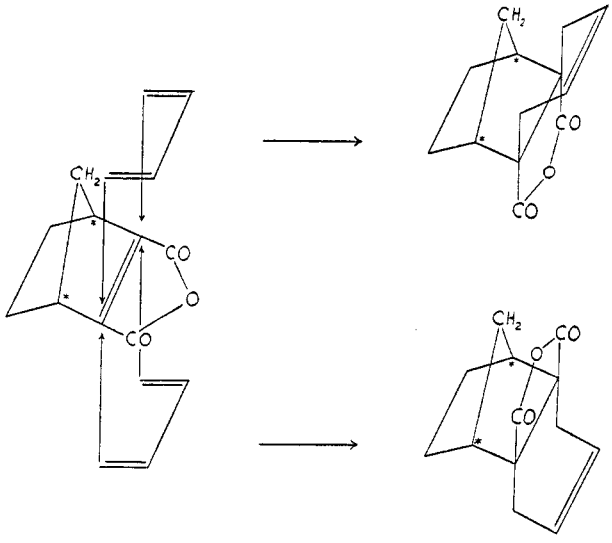
The configuration which would lead to formation of an endo-isomer is the following:



Qualitatively at least, it may be seen that the orientation leading to formation of the exo-isomer permits greater accumulation of double bonds just prior to consummation of addition than does the orientation leading to formation of the endo-isomer.

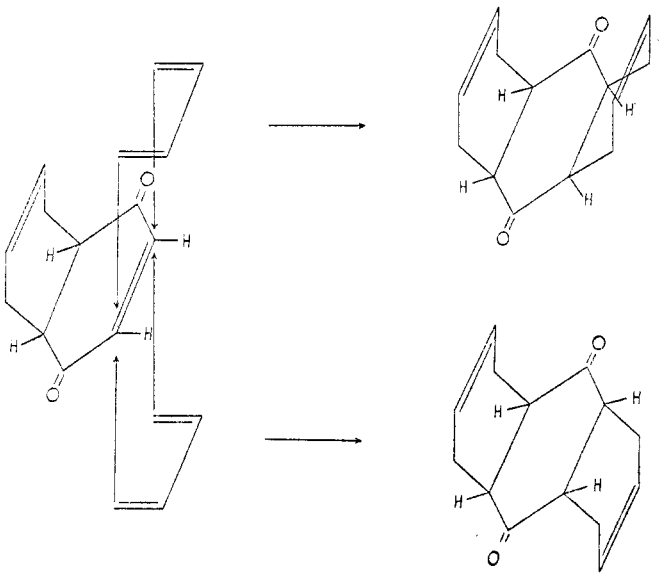
This rule of maximum accumulation of double bonds applies not only to aliphatic carbonylenic dienophiles, but also to additions to quinones, acetylenic dienophiles, diene dimerizations, etc. Thus, cyclopentadiene dimer is the endo-isomer.

The third heading under which a portion of the stereochemical phenomena of the diene synthesis may be grouped is covered by the question as to whether the diene adds "above" or "below" the dienophilic double bond. The question is of no importance in the majority of diene syntheses, but becomes a factor when additions of dienes to dienophiles such as the adduct of equimolar quantities of cyclopentadiene with an acetylenic dienophile are considered. In general, the question arises when the diene synthesis occurs with a dienophile possessing asymmetric substituents. In the three-dimensional sketch below, the asymmetric centers are marked with asterisks:



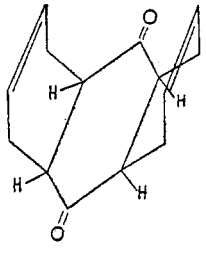
In the case cited, the addition of a diene (such as butadiene) to the adduct of 1 mole of cyclopentadiene to an acetylenic dienophile, the addition proceeds exo with respect to the methylene bridge. This appears to be generally true; while the endomethylene bridge of cyclopentadiene dimer is endo with respect to the activating double bond, further additions of cyclopentadiene to the dimer (which occur at the double bond of the 1:2:2-bicycloheptene ring) resulting in the production of cyclopentadiene trimer, tetramer, etc., result in compounds all of the endomethylene bridges of which are on the same side of the ring system. Hence the dimerization is an endo addition, while further additions are of the exo variety.

Allied to this same type of possible addition are the cases of the bis-diene quinones. *p*-Benzoquinone may add 2 moles of a diene; the addition of the first mole occurs much more rapidly than the addition of the second mole. Since the only rule involved in the determination of structural configuration of the product is the *cis* principle, the bis-diene quinone question may be resolved into a question of the direction of addition of dienes to quinones which have one aliphatic ring fused directly to the *p*-benzoquinone ring, and which have a singly bound pair of fusion atoms. A good example of this is the addition of butadiene to monobutadienequinone (1a,4a,5,8-tetrahydro-1,4-naphthoquinone):

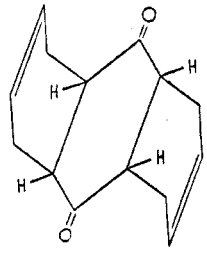


It is known that the bisbutadienequinone (1,4,5,8,1a,4a,5a,8a-octahydro-9,10-anthraquinone) is formed through exclusive *cis*-addition of both molecules of butadiene. This is shown in a number of ways, one being that the reduced quinone (dodecahydroanthraquinone) is oxidizable, giving adipic acid and *cis*-hexahydrophthalic acid without the formation of detectable quantities of the *trans*-isomer. Had both molecules of butadiene added *trans*, or had either one added *trans*, detectable quantities of *trans*-hexahydrophthalic acid would have been formed.

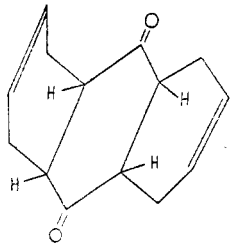
The dodecahydroanthraquinone may be isomerized by alkali or by acetic anhydride to dodecahydroanthraquinone of a different variety. This form would be obtained on reduction of one of the two possible *trans*-addition products of butadiene to *p*-benzoquinone if such actually occurred; oxidation yields adipic and *trans*-hexahydrophthalic acids exclusively. Hence this quinone must be either VI or VII, so no detectable amount of *cis*-hexahydrophthalic acid is found, as would be the case with quinone V.



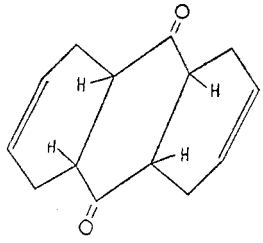
III



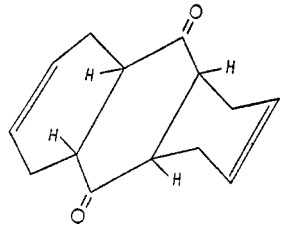
IV



V



VI



VII

Quinone III is of a configuration which would be formed by *cis*-addition of both molecules of butadiene, and the two external rings bear a *cis* relationship to each other. Quinone IV is of a configuration formed in a similar manner, but the external rings are *trans* to each other. Alder and Stein designate these two configurations by the terms, "an-*cis*" and "an-*trans*", respectively. Since both quinones are formed by reduction of *p*-benzoquinonebutadiene in which both molecules of butadiene have added *cis*, III is termed *cis*-,*cis*-,an-*cis*-dodecahydroanthraquinone. Likewise, IV is *cis*-,*cis*-,an-*trans*-dodecahydroanthraquinone. VI is *trans*-,*trans*-,an-*cis*-dodecahydroanthraquinone, and VII is *trans*-,*trans*-,an-*trans*-dodecahydroanthraquinone.

As previously stated, it is known that the bisbutadienequinone formed from *p*-benzoquinone and butadiene is a *cis*-,*cis*-quinone, but it is not known whether it is the an-*cis*- or the an-*trans*-isomer. A guess as to which of these possibilities is actually the case may be based on (*a*) the rule of concentration of double bonds, assuming that the double bond of monobutadiene-*p*-benzoquinone which is in the reduced benzene ring is the deciding factor, and (*b*) on the exo addition of dienes to substances such as 3,6-endomethylene-3,4,5,6-tetrahydrophthalic acid. These considerations lead one to suggest tentatively that the second molecule of butadiene adds exo and that the bisbutadienequinone which is

actually formed is the *cis*-,*cis*-,an-*cis*-isomer, rather than the *cis*-,*cis*-,an-*trans*-form.

Another phase of isomerism and stereochemistry of the diene synthesis which was not discussed by Alder and Stein in their treatise (27) is the formation of one or another or a mixture of isomers when an unsymmetrical diene, such as piperylene, reacts with an unsymmetrical dienophile, such as crotonaldehyde or acrylic acid. In the first place, with acrylic acid one may obtain either tetrahydro-*o*- or tetrahydro-*m*-toluic acid, each of which may be either *cis* or *trans*; the *trans*-isomer may exist in two optically active forms. No general rule appears to have been stated as to which of the possibilities one may obtain in such additions. Further, no attempt has been made to explain the apparent differences in the reactivity of the *cis*- and *trans*-piperylenes toward maleic anhydride (see page 349). The observation should be checked and the unreactive residue, if any, should be demonstrated to be piperylene or at least a methylbutadiene (see footnote 1).

XVII. DIENANALYSIS

Dienanalysis is, as its name implies, analysis for dienes. The diene number is a quantity defined by Kaufmann and Baltes (257) as $1.269A/W$, where A is the volume in cubic centimeters of tenth-normal alkali which *would have been* necessary to neutralize the maleic anhydride which reacted with W grams of the sample being analyzed. Thus the diene number is a measure of the amount of dienes present in a mixture or, if the diene is pure, it is a measure of the weight per cent of the compound which is in the form of the C=C—C=C group and also a measure of its molecular weight.

The C=C—C=C group itself has a theoretical diene number of 528.75, as do the groups C≡C—C≡C and C≡C—C=C. When the first of these last two groups reacts with maleic anhydride, a phthalic acid derivative should be formed, and the reaction ceases with the addition of 1 mole of maleic anhydride. On the other hand, the C≡C—C=C group forms a cyclic allene which rearranges to a 1,3-cyclohexadiene. The last named is capable of adding another mole of maleic anhydride; if conditions are such that this may occur quantitatively, the C≡C—C=C group will show a diene number of 1057.5, which is much the highest of them all. Accordingly, vinylacetylene is the compound which should have the highest diene number of the simpler compounds (a compound such as octa-1,7-dien-3,5-diyne would have a slightly higher diene number) when it adds 2 moles of maleic anhydride. This number is 976.2. If, on the other hand, conditions are such that only 1 mole of anhydride is added, the observed diene number would be 488.1. Of the compounds which add 1 mole of maleic anhydride only, 1,3-butadiyne has the highest diene number, 507.6. Butadiene has a diene number of 470, which is the highest diene number obtained for all true dienes.

If the diene under consideration will add but 1 mole of maleic anhydride, the diene number will be equal to 25,380 divided by the molecular weight of the diene. If 2 moles are added, then the diene number will be equal to 50,760 divided by the molecular weight.

Kaufmann and Baltes have developed a general method for determination of diene number which is designed particularly for fat analysis, though it may be applied to other compounds with suitable modifications. It consists essentially of heating a 0.1-g. sample of glyceride with excess of a known acetone solution of maleic anhydride for a period of 20 hr., using a sealed tube for the reaction. The excess maleic anhydride is determined by one of two methods: (*a*) by titration of the filtered aqueous extract of the product with standard alkali, or (*b*) by addition of an excess of a mixture of potassium iodide and iodate and determination of the iodine formed by thiosulfate titration. Two equivalents of thiosulfate are required per mole of excess anhydride used (257, 260).

Diene numbers have been determined for a number of fats and terpinoid bodies (233, 257, 258, 259, 260, 261, 262). These range from zero for synthetic triolein, palm-kernel oil, and cacao butter to 46.0 for bay oil. Oils such as cottonseed and peanut, which do not contain dienic glycerides as far as is known, also show diene numbers. These numbers are usually quite low, being in the range of 5 to 10, and are provisionally attributed to the presence of dienic substances in the nonsaponifiable fractions. There is also a possibility that the dienic esters which might be present in the original fat undergo alteration on saponification, for the acids obtained by the saponification of such fats do not show diene numbers. The method is more reliable for dienic glycerides than analysis of fats with iodine or thiocyanogen, for these two methods show other unsaturated acids as well as conjugated dienic acids (258, 259).

Accordingly, the iodine and thiocyanogen numbers of the Chinese wood oils indicated about 10 per cent more eleostearic acid than did the diene number. This discrepancy was found to be due to linolic acid and oleic acid. A typical sample gave the following analysis: 74.5 per cent eleostearic acid, 9.7 per cent linolic acid, 8 per cent oleic acid, 3.3 per cent saturated acids, 0.1 per cent unsaponifiable matter, and 4.5 per cent glycerol residues (258). The oil of the pits of the oiticaca tree showed a similar discrepancy between the results obtained by the diene analysis method and those obtained by the iodine or thiocyanogen method (259). Further analysis of a sample showed 70 per cent licanic acid, 15.2 per cent unsaturated nonconjugated acids, 9.9 per cent saturated acids, 0.4 per cent nonsaponifiable matter, and 4.5 per cent glycerol residues.

Dienanalysis has been applied to a limited extent in the petroleum industry. Birch and Scott (91) and Grosse-Oetringhaus (231) studied the quantitative determination of dienic materials in petroleum hydrocarbons, with emphasis on products from cracking and polymerization processes. Grosse-Oetringhaus developed a procedure for the determination which consisted in heating the hydrocarbon mixture with an excess of a solution of maleic anhydride in xylene (the strength of this solution was about 0.2 molar). In order to minimize polymerization and possible reactions between ethylenic hydrocarbons and maleic anhydride, the temperature was not allowed to rise over 100°C. Results were not very consistent, the diene number tending to increase with reaction time, which was varied from 5 to 30 hr. Toluene gave unreliable results.

A gasometric method of analysis of gases containing reactive dienes was developed by Tropsch and Mattox (343), who absorbed the diene in a special

absorption pipet containing molten maleic anhydride. Their method was employed by Robey (309), who analyzed piperylene obtained from cracked gas-oil and also by dehydrochlorination of chloropentanes. Absorption ceased before theoretical amounts were absorbed, and this phenomenon was ascribed to differences in reactivities between the *cis*- and *trans*-forms (see pages 350 and 504).

An obvious application of dienanalysis is the determination of the purity of a sample of diene. A sample of eucalyptus oil was found to contain 18.8 per cent of *l*-α-phellandrene, and increase of the proportion of *l*-α-phellandrene during the process of purification could be followed conveniently by means of dienanalysis. Variation of the length of reaction time made but little difference after the first 2 hr., for a sample of commercial α-phellandrene gave a diene number of 98.0 in a 2-hr. reaction period and a diene number of 99.2 in a 10-hr. reaction period. This corresponded to 53 per cent phellandrene. A commercial myrcene (262) gave a diene number of 134.3 in 30 min. reaction time and a number of 144.1 in 90 min. reaction time. A number of 145.1 was observed after 135 min. reaction time, corresponding to 77.4 per cent pure myrcene. α-Terpinene reacts quantitatively with maleic anhydride at room temperature, and may be estimated and detected.

XVIII. SYNTHETIC AND MISCELLANEOUS APPLICATIONS OF THE DIENE SYNTHESIS

To close this review of the diene synthesis, some of the various applications of the diene synthesis in synthetic and other uses will be shown. A large number of the studies which were reviewed were concerned chiefly with syntheses of certain desired substances, and the diene synthesis was merely a convenient tool with which to achieve these ends.

Polyakova (303, 421) utilized the diene synthesis for the preparation of pure anthracene from coal-tar anthracene. The crude material was heated with over twice the theoretical quantity of maleic anhydride at 140–150°C. for 4 hr. The product was then digested with 10 per cent alkali and filtered. The filtrate was acidified with sulfuric acid, and the adduct was collected, washed, dried, and heated at 300°C. The sublimate, consisting of a mixture of maleic anhydride and anthracene, together with small amounts of re-formed adduct, was extracted with 10 per cent alkali. The residue was anthracene of 95–97 per cent purity. Dermer and King (401) employed a similar method, conducting the distillation of the adduct from soda lime, thereby removing maleic anhydride and preventing re-formation of adduct.

Billing (90) heated crude, gaseous maleic anhydride at 160–200°C. with terpinene, pinene, or rosin, producing resinous products. Resins from rosin and maleic anhydride have been described by Powers (304). The American Cyanamid Co. (53) has used polyterpenes.

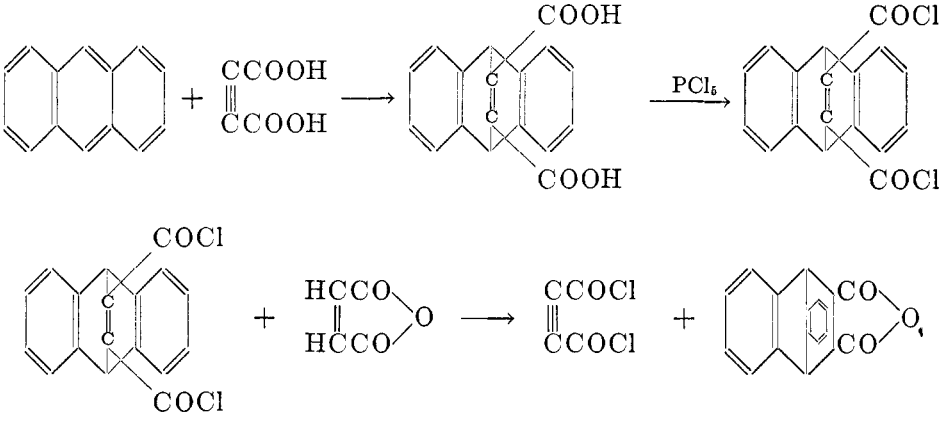
Bradley and Johnston (396) state that thermal polymerization of drying oils is largely a Diels–Alder reaction which is preceded by rearrangement of isolated double bonds to a conjugated system. Alekseeva (384, 385) states that the

diene synthesis accounts for a considerable portion of the reactions in the copolymerizations of butadiene with styrene and with methacrylonitrile.

Martin, Gruse, and Lowy (292) studied the effect on gum formation in cracked petroleum distillates after dienes were removed by maleic anhydride.

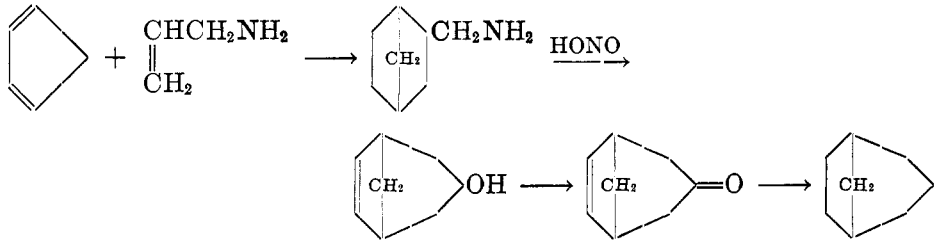
Pirsch (302) offered circumstantial evidence for Alder and Stein's formulae for the polymers of cyclopentadiene. He employed cyclopentadiene dimer, the dihydro, and the tetrahydro derivatives as solvents for micromolecular-weight determinations. As in the cases of camphor and related substances, the molecular depressions were high in all instances, being 46.2°, 45.4° and 35°, respectively. Pirsch has correlated molecular depressions with structures of various compounds used as solvents which belong to the isocamphane group.

As may have been evident, the various adducts discussed in this review have shown differing degrees of heat stability, which range from the rather highly stable adducts of the simple dienes with maleic anhydride to the adducts of fulvenes and arylated anthracenes which dissociate in solution to their generators in reactions which obey the law of mass action. This variance in adduct stability was made useful in a most ingenious preparation of the acid chloride of acetylenedicarboxylic acid (172). When this acid is treated with phosphorus pentachloride, there is obtained chlorofumaroyl dichloride. The method successfully employed was as follows: The adduct of anthracene with acetylene dicarboxylic acid was treated with phosphorus pentachloride, thus forming the adduct acid dichloride in 33 per cent yield. On heating this acid chloride with maleic anhydride, displacement of dienophile occurred, and the products were the acid chloride of acetylenedicarboxylic acid and the anthracene–maleic anhydride adduct. Some interaction between the products did occur, for there were also formed fumaroyl dichloride and chloropropiolyl chloride. The series of reactions is indicated below:

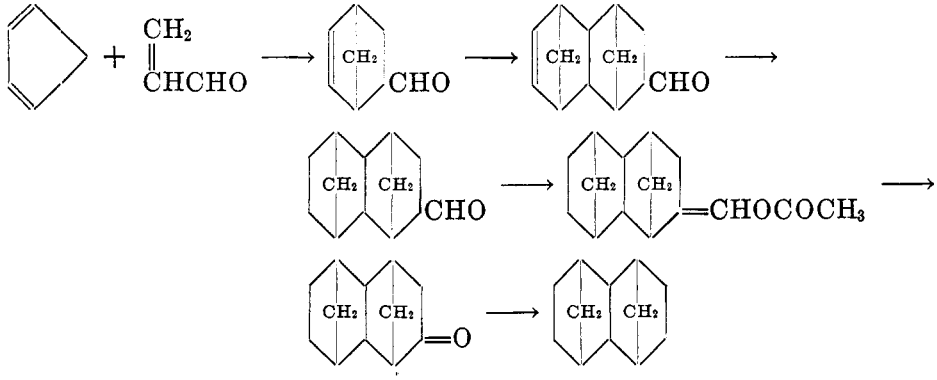


Alder and Windemuth (41, 42) used the diene synthesis in the preparation of bridged hydrocarbons. The first was bicyclo-(1:2:3)-octane, prepared by treatment of the allylamine adduct of cyclopentadiene with nitrous acid, oxida-

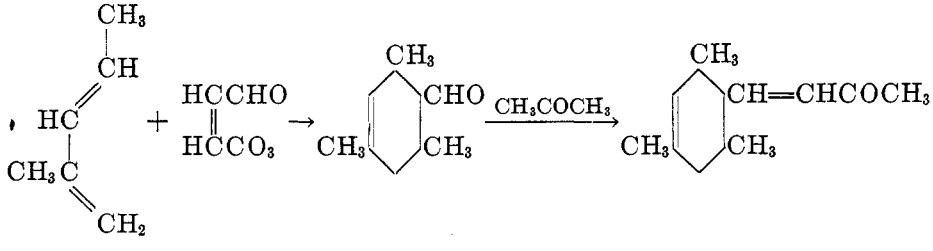
tion of the resulting alcohol to the corresponding ketone, and then reduction to the hydrocarbon:



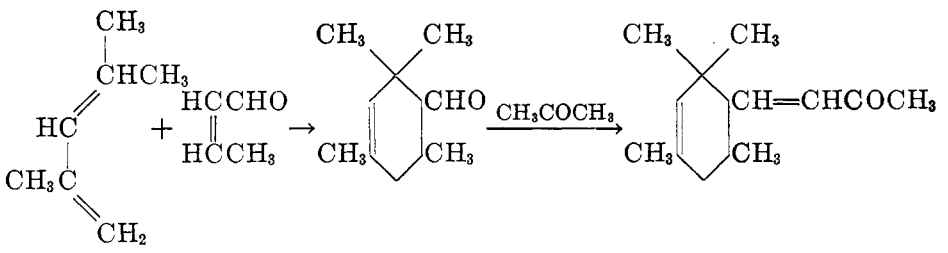
The second synthesis (42) was that of 1,4,5,8-bis(endomethylene)decalin. The acrolein adduct of cyclopentadiene was caused to add a second mole of cyclopentadiene. The resulting aldehyde was reduced and then converted into the enol acetate, oxidation of which gave a cyclic ketone. This ketone was reduced by sodium and alcohol at 200°C. to give the hydrocarbon:



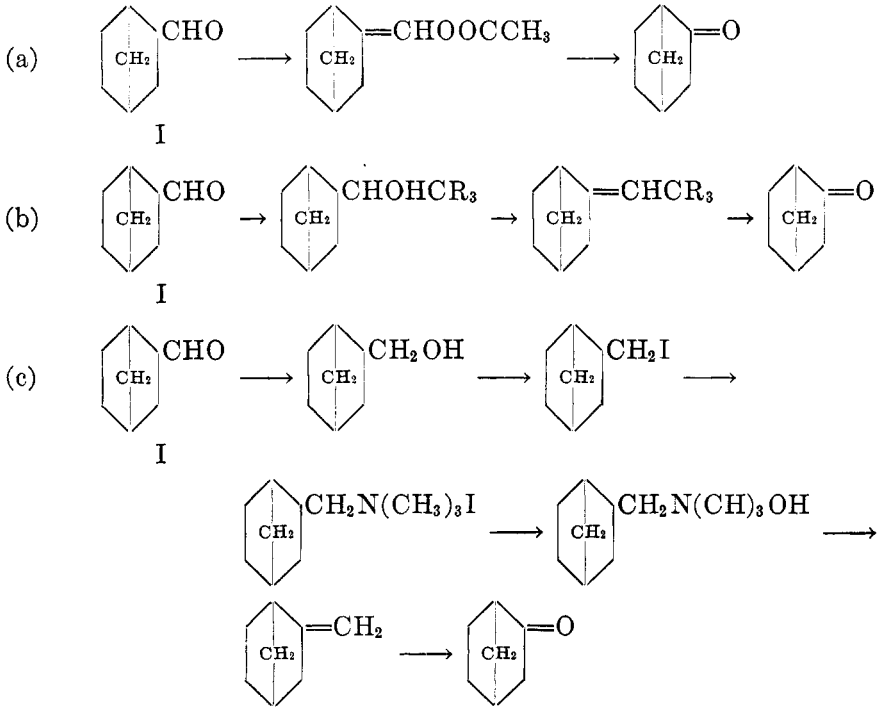
These two hydrocarbons are closely related to the terpinoid bodies. A number of such materials have been synthesized using the diene synthesis in one stage or other of their syntheses. A "pseudo-irone" was prepared by Diels and his students (144) by the reaction of crotonaldehyde with 1,3-dimethylbutadiene, followed by condensation of the adduct with acetone:



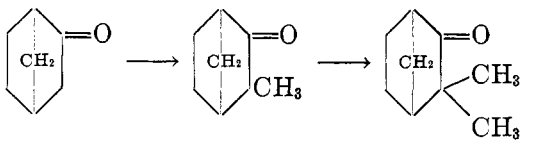
A similar product, containing an additional methyl group, was synthesized by employing 1,1,3-trimethylbutadiene in place of 1,3-dimethylbutadiene:



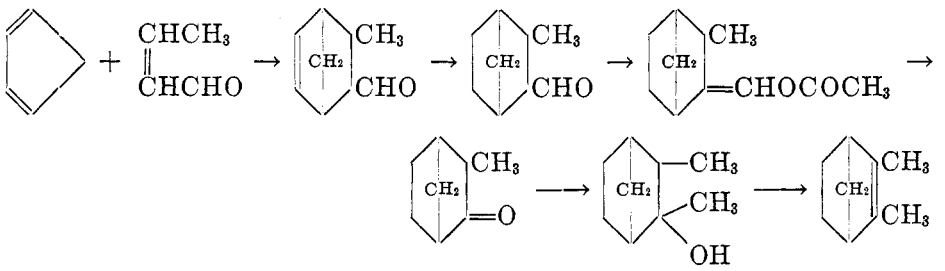
Norcamphor (144, 150) was synthesized by the reaction of acrolein with cyclopentadiene and reduction of the resulting adduct to the fully saturated aldehyde (I). The aldehyde group was eliminated and norcamphor was the end product. There are at least three ways of eliminating the aldehyde group, such as (*a*) treatment with acetic anhydride and sodium acetate to form the enol acetate, followed by oxidation; (*b*) treatment with a Grignard reagent, dehydration of the carbinol thus formed, and splitting of the resulting olefin with ozone or some other oxidizing agent; and (*c*) a roundabout method used by Diels and Alder, which consists in reduction of the saturated aldehyde to the corresponding alcohol, formation of the corresponding iodide by treatment with hydrogen iodide, formation of a quaternary iodide by treatment with trimethylamine, pyrolysis with alkali to yield norcamphene, and finally with ozone to yield norcamphor:



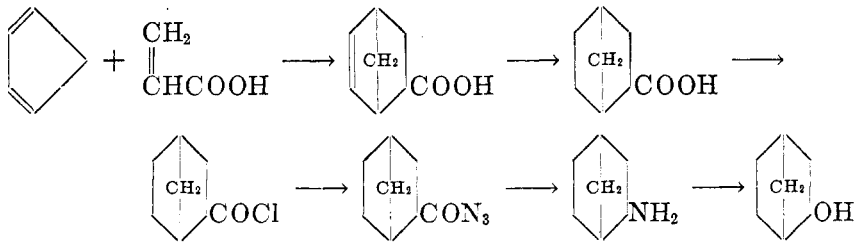
Camphenilone was synthesized from the norcamphor by double treatment with sodium amide and methyl iodide.



Santene (150) was synthesized by the reaction of cyclopentadiene with crotonaldehyde, and the adduct was reduced to the saturated aldehyde. This was converted into methylnorcamphor by means of acetic anhydride and sodium acetate, followed by ozonization. Methylmagnesium iodide reacted with methylnorcamphor to give γ-santenol, which was dehydrated to santene by heating with potassium sulfate:



Norborneol (37) was synthesized by reduction of the adduct of cyclopentadiene and acrylic acid to 2,5-endomethylenehexahydrobenzoic acid. This acid was converted into its acid chloride, and thence into the acid azide. The azide was decomposed into norbornylamine by the usual Curtius degradation. The norbornylamine yielded norborneol on treatment with nitrous acid. In a similar fashion, an amino derivative of norbornylamine (1,2-diaminobicyclo-1:2:2-heptane) may be made beginning with the adduct of cyclopentadiene and maleic acid.



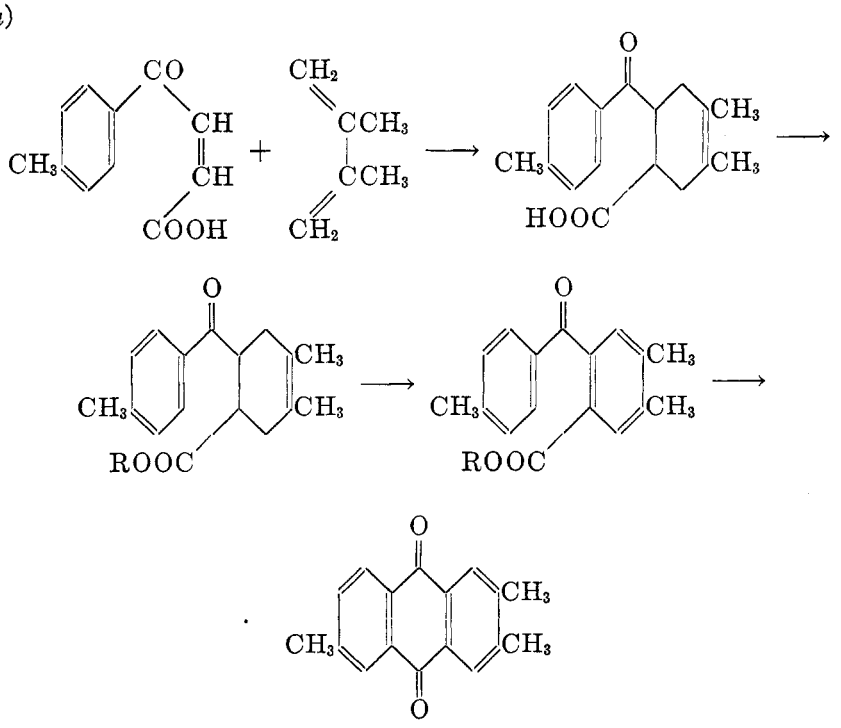
Two terpene preparations, those of *dl*-limonene and diprene, have been discussed under the heading "Dimerization". A considerable number of other preparations have been either discussed or else mentioned briefly in connection with other diene reactions. In the main, the syntheses presented in this section up to this point have not been discussed in this review in connection with other diene syntheses. From this point on, there will be considered representative synthetic methods employing the diene reaction which have been alluded to previously.

2,5-Dimethylhexa-1,5-dien-3-yne (100), was employed for the synthesis of 1,5-dimethylnaphthalene, as was indicated on pages 380 and 386. The reactions involved in the degradation of the adduct seem rather obvious; they are dehydrogenation and decarboxylation.

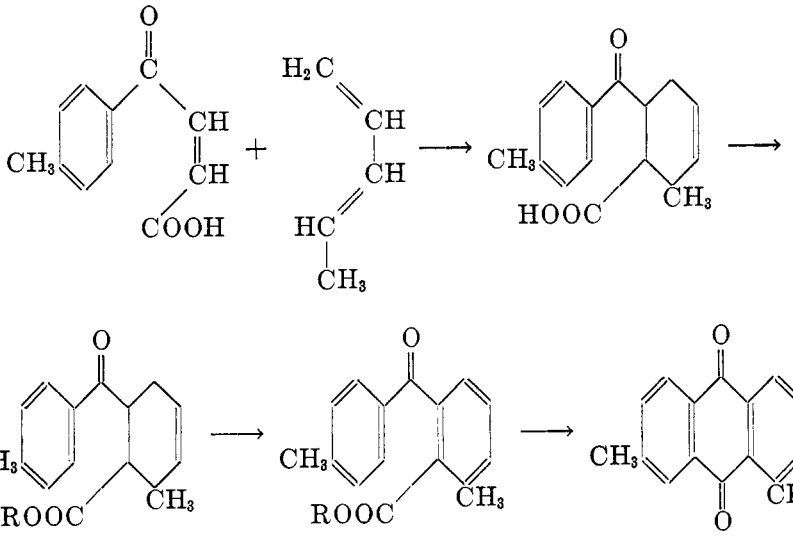
Dufraisse and Compagnon (185) synthesized rubrene from α-naphthoquinone and diphenylisobenzofuran; the diene itself was formed by a synthesis involving the diene reaction (this has been rather well covered on page 477).

Fieser, Fieser, and Herschberg (211, 215) have employed the diene synthesis in the preparation of substituted anthraquinones. In general, an aroylacrylic acid was allowed to react with a diene. The adduct was converted into an ester which was dehydrogenated to a 2-aroylbenzoic acid ester. This ester was then cyclized to give the desired anthraquinone. The aroylacrylic acid was prepared by condensation of the appropriate aromatic hydrocarbon with maleic anhydride, using aluminum chloride as the condensing agent. Unless both the diene and aroylacrylic acid were symmetrically substituted, or unless the aroylacrylic acid had one of its ortho-positions blocked if unsymmetrically substituted, uncertainty as to the structure of the resulting quinone will arise. This may be illustrated by (*a*) the reactions of *p*-toluylacrylic acid with 2,3-dimethylbutadiene, (*b*) the reactions of *p*-toluylacrylic acid with piperylene, (*c*) the reactions of *m*-toluylacrylic acid with 2,3-dimethylbutadiene, and (*d*) the reactions of 2,4-dimethylbenzoylacrylic acid with butadiene:

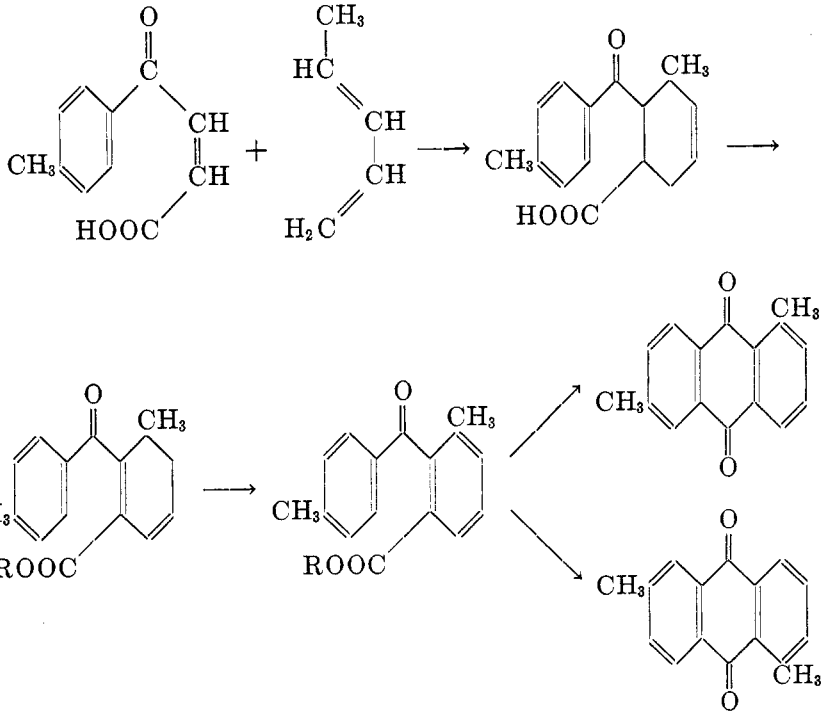
(*a*)



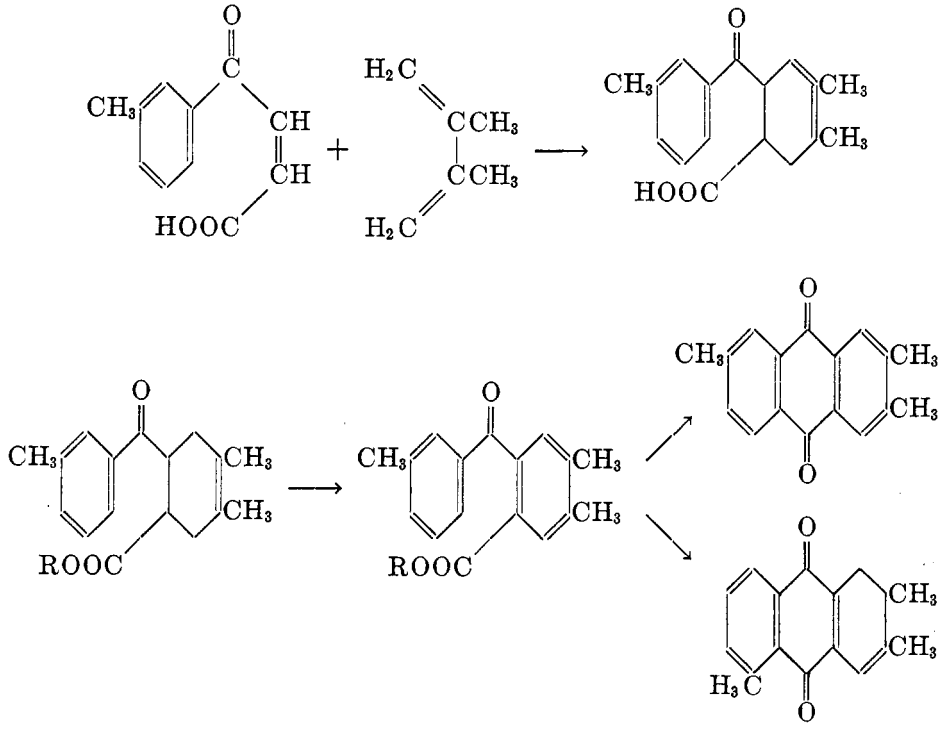
(*b*)



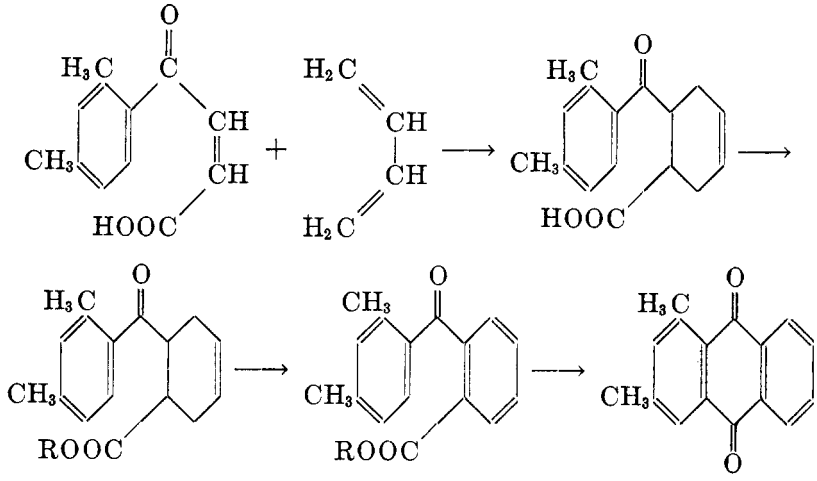
or



(*c*)

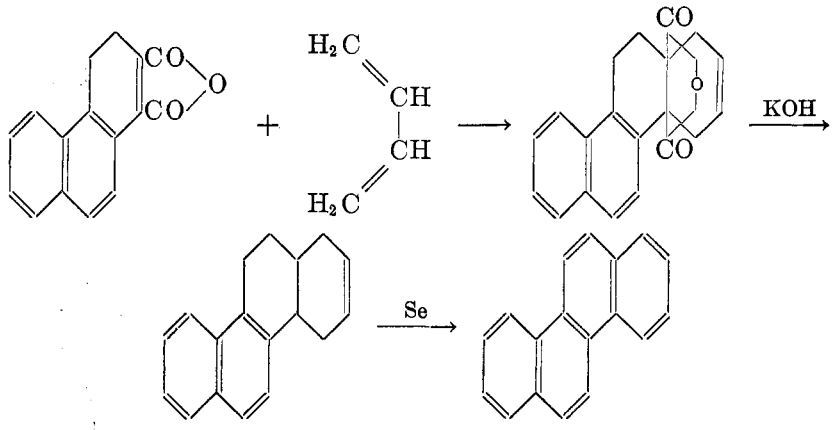


(*d*)



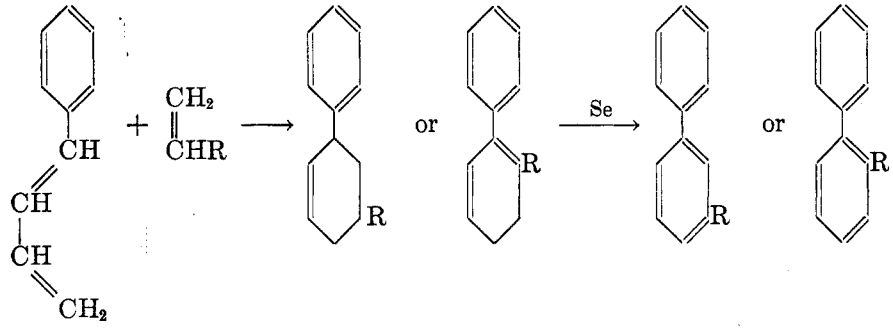
Certain of the above instances have been discussed by Fieser, Fieser, and Herschberg (213); those which they did not discuss are examples selected by the author of this review in order to show the possibilities of production of isomeric substances.

Fieser and Herschberg (213) synthesized chrysene by a series of reactions which involve the diene synthesis as one of the steps:

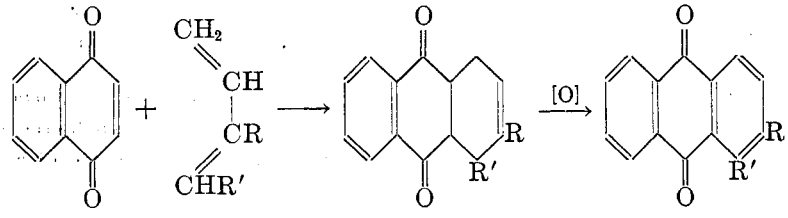


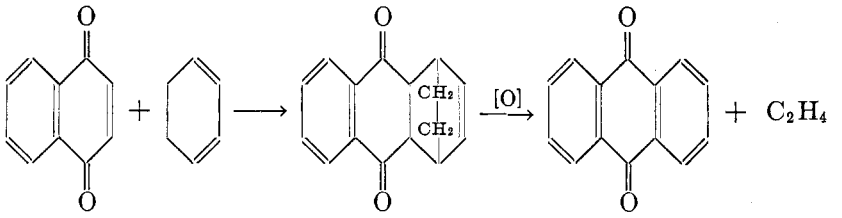
It may be seen that this method is perfectly general, for by use of the appropriate diene any desired chrysene possessing substituents in one of the external rings may be synthesized.

Substituted biphenyls may be produced from 1-phenylbutadiene via the diene synthesis:



Substituted anthraquinones may be obtained by a more direct method than that used by Fieser. α-Naphthoquinone may be caused to react with suitably substituted butadienes or cyclohexadienes. The adduct is heated in air, whereupon oxidation occurs (the adduct with cyclohexadiene will split out olefin simultaneously) and a substituted anthraquinone is obtained.





Fieser and Novello (406) have prepared 4,10-ace-1,2-benzanthracene, starting with 1,2,3,6-tetrahydrophthalic anhydride.

The valuable aid of Mr. Angelo J. Longo in furnishing a number of references which had been overlooked by the author and in proofreading the manuscript and galleys is hereby gratefully acknowledged.

REFERENCES

(1) ACREE, F., JR., AND LAFORGE, F.: J. Org. Chem. **4,** 569 (1939).
(2) ACREE, F., JR., AND LAFORGE, F.: J. Org. Chem. **5,** 48 (1940).
(3) ADAMS, R., AND GOLD, M.: J. Am. Chem. Soc. **62,** 56 (1940).
(4) ADAMS, R., AND GOLD, M.: J. Am. Chem. Soc. **62,** 2038 (1940).
(5) ADAMS, R., AND GRUBER, E.: J. Am. Chem. Soc. **60,** 2792 (1938).
(6) ADAMS, R., AND WEARN, R.: J. Am. Chem. Soc. **62,** 1233 (1940).
(7) ADLER, E.: Arkiv. Kemi, Mineral. Geol. **11B,** No. 49 (1935).
(8) ALDER, K.: Ber. **71B,** 2210 (1938).
(9) ALDER, K., AND BACKENDORF, K.: Ann. **535,** 101 (1938).
(10) ALDER, K., AND BACKENDORF, K.: Ann. **535,** 113 (1938).
(11) ALDER, K., AND BACKENDORF, K.: Ber. **71B,** 2199 (1938).
(12) ALDER, K., AND HOLZRICHTER, H.: Ann. **524,** 145 (1936).
(13) ALDER, K., AND RICKERT, H.: Ann. **524,** 180 (1936).
(14) ALDER, K., AND RICKERT, H.: Ber. **70B,** 1354 (1937).
(15) ALDER, K., AND RICKERT, H.: Ber. **70B,** 1364 (1937).
(16) ALDER, K., AND RICKERT, H.: Ber. **71B,** 373 (1938).
(17) ALDER, K., AND RICKERT, H.: Ber. **71B,** 379 (1938).
(18) ALDER, K., AND RICKERT, H.: Ber. **72B,** 1983 (1939).
(19) ALDER, K., AND RICKERT, H.: Ann. **543,** 1 (1939).
(20) ALDER, K., RICKERT, H., AND WINDEMUTH, E.: Ber. **71B,** 2451 (1938).
(21) ALDER, K., AND SCHNEIDER, S.: Ann. **524,** 189 (1936).
(22) ALDER, K., AND STEIN, G.: Ann. **496,** 197 (1932).
(23) ALDER, K., AND STEIN, G.: Ann. **501,** 247 (1933).
(24) ALDER, K., AND STEIN, G.: Ber. **67B,** 373 (1934).
(25) ALDER, K., AND STEIN, G.: Ber. **67B,** 613 (1934).
(26) ALDER, K., AND STEIN, G.: Angew. Chem. **47,** 837 (1934).
(27) ALDER, K., AND STEIN, G.: Angew. Chem. **50,** 510 (1937).
(28) ALDER, K., STEIN, G., BUDDENBROOK, R. V., ECKHARDT, W., FRERCKS, W., AND SCHNEIDER, S.: Ann. **514,** 1 (1934).
(29) ALDER, K., STEIN, G., ECKHARDT, W., BUDDENBROOK, R. V., AND SCHNEIDER, S.: Ann. **504,** 216 (1933).
(30) ALDER, K., STEIN, G., AND FINZENHAGEN, H.: Ann. **485,** 211 (1931).
(31) ALDER, K., STEIN, G., AND FINZENHAGEN, H.: Ann. **485,** 223 (1931).
(32) ALDER, K., STEIN, G., AND FRIEDRICHSEN, W.: Ann. **501,** 1 (1933).
(33) ALDER, K., STEIN, G., FRIEDRICHSEN, W., AND HORNUNG, K.: Ann. **515,** 165 (1934).
(34) ALDER, K., STEIN, G., AND GRASSMANN, W.: Ann. **504,** 205 (1933).

(35) ALDER, K., STEIN, G., LIEBMANN, M., AND ROLLAND, E.: Ann. **514**, 197 (1934).
(36) ALDER, K., STEIN, G., REESE, J., AND GRASSMANN, W.: Ann. **496**, 204 (1932).
(37) ALDER, K., STEIN, G., ROLLAND, E., AND SCHULZE, G.: Ann. **514**, 211 (1934).
(38) ALDER, K., STEIN, G., AND SCHNEIDER, S.: Ann. **515**, 185 (1934).
(39) ALDER, K., STEIN, G., SCHNEIDER, S., LIEBMANN, M., ROLLAND, E., AND SCHULZE, G.: Ann. **525**, 183 (1936).
(40) ALDER, K., AND WINDEMUTH, E.: Ber. **71B**, 1939 (1938).
(41) ALDER, K., AND WINDEMUTH, E.: Ber. **71B**, 2404 (1938).
(42) ALDER, K., AND WINDEMUTH, E.: Ber. **71B**, 2409 (1938).
(43) ALDER, K., AND WINDEMUTH, E.: Ann. **543**, 28 (1939).
(44) ALDER, K., AND WINDEMUTH, E.: Ann. **543**, 41 (1939).
(45) ALDER, K., AND WINDEMUTH, E.: Ann. **543**, 56 (1939).
(46) ALEKSEEVA, E.: J. Gen. Chem. (U. S. S. R.) **9**, 1586 (1939).
(47) ALLEN, C., BELL, A., BELL, A., AND VAN ALLAN, J.: J. Am. Chem. Soc. **62**, 656 (1940).
(48) ALLEN, C., AND GILMAN, L.: J. Am. Chem. Soc. **58**, 937 (1936).
(49) ALLEN, C., AND SHEPS, L.: Can. J. Research **11**, 171 (1934).
(50) ALLEN, C., AND SPANAGEL, E.: J. Am. Chem. Soc. **54**, 4338 (1932).
(51) ALLEN, C., AND SPANAGEL, E.: Can. J. Research **8**, 414 (1933).
(52) ALLEN, C., AND SPANAGEL, E.: J. Am. Chem. Soc. **55**, 3773 (1933).
(53) AMERICAN CYANAMID COMPANY: French patent 809,329 (March 1, 1937).
(54) ARBUZOV, B.: Ber. **67B**, 563 (1934).
(55) ARBUZOV, B.: J. Gen. Chem. (U. S. S. R.) **2**, 806 (1932).
(56) ARBUZOV, B.: J. Gen. Chem. (U. S. S. R.) **3**, 21, 28 (1933); Ber. **67B**, 563 (1934).
(57) ARBUZOV, B.: Ber. **67B**, 1946 (1934).
(58) ARBUZOV, B.: Ber. **68B**, 1435 (1935).
(59) ARBUZOV, B., AND NIKANOROV, K.: J. Gen. Chem. (U. S. S. R.) **10**, 649 (1940).
(60) ARBUZOV, B., AND RAFIKOV, S.: J. Gen. Chem. (U. S. S. R.) **7**, 2195 (1937).
(61) ARBUZOV, B., SALMINA, E., AND SHAPSHINSKAYA, O.: Trans. Butlerov. Inst. Chem. Tech. Kazan **No. 2 (1934)**, 9.
(62) ARBUZOV, B., AND SPEKTERMANN, S.: Trans. Kirov. Inst. Chem. Tech. Kazan, **No. 8 (1940)**, 21.
(63) ARBUZOV, B., ZINOV'EVA, Z., AND FINK, I.: J. Gen. Chem. (U. S. S. R.) **7**, 2278 (1937).
(64) ASANO, M., AND KANEMATSU, T.: Ber. **65B**, 1602 (1932).
(65) BACHMANN, W.: J. Org. Chem. **3**, 434 (1938).
(66) BACHMANN, W., AND KLOETZEL, M.: J. Am. Chem. Soc. **60**, 481 (1938).
(67) BACHMANN, W., AND KLOETZEL, M.: J. Am. Chem. Soc. **60**, 2204 (1938).
(68) BACON, R., AND FARMER, E.: J. Chem. Soc. **1937**, 1065.
(69) BACON, R., AND RUZICKA, L.: Chemistry & Industry **55**, 546 (1936).
(70) BAEYER, A. VON: Ber. **27B**, 810 (1894).
(71) BARNETT, E.: J. Chem. Soc. **1935**, 1326.
(72) BARNETT, E., GOODWAY, N., HIGGINS, A., AND LAWRENCE, C.: J. Chem. Soc. **1934**, 1224.
(73) BARNETT, E., GOODWAY, N., AND WEEKES, E.: J. Chem. Soc. **1935**, 1102.
(74) BARNETT, E., AND LAWRENCE, C.: J. Chem. Soc. **1935**, 1104.
(75) BARTLETT, P., AND COHEN, S.: J. Am. Chem. Soc. **62**, 1183 (1940).
(76) BARTLETT, P., AND WOODS, G.: J. Am. Chem. Soc. **62**, 2933 (1940).
(77) BENFORD, G., KAUFMANN, H., KHAMBATA, B., AND WASSERMANN, A.: J. Chem. Soc. **1939**, 381.
(78) BENFORD, G., KHAMBATA, B., AND WASSERMANN, A.: Nature **139**, 669 (1937).
(79) BENFORD, G., AND WASSERMANN, A.: J. Chem. Soc. **1939**, 362, 367.
(80) BERCHET, G., AND CAROTHERS, W.: J. Am. Chem. Soc. **55**, 2004 (1933).
(81) BERGEL, F., AND WIDMANN, E.: Ann. **467**, 76 (1928).
(82) BERGMANN, E.: J. Chem. Soc. **1935**, 1359.
(83) BERGMANN, E.: J. Chem. Soc. **1938**, 1147.

(84) BERGMANN, E., AND BERGMANN, F.: J. Am. Chem. Soc. **59**, 1443 (1937).
(85) BERGMANN, E., AND BERGMANN, F.: J. Org. Chem. **3**, 125 (1938).
(86) BERGMANN, F.: J. Am. Chem. Soc. **60**, 2811 (1938).
(87) BERGMANN, F., AND BERGMANN, E.: J. Am. Chem. Soc. **62**, 1699 (1940).
(88) BERGMANN, F., AND WEINBERG, Z.: J. Org. Chem. **6**, 134 (1941).
(89) BERLIN, A., AND SHERLIN, S.: J. Gen. Chem. (U. S. S. R.) **8**, 16 (1938).
(90) BILLING, W.: U. S. patent 2,126,944 (August 16, 1938).
(91) BIRCH, S., AND SCOTT, W.: Ind. Eng. Chem. **24**, 49 (1932).
(92) BLOMQUIST, A., AND MARVEL, C.: J. Am. Chem. Soc. **55**, 1655 (1933).
(93) BOCKEMULLER, W.: Angew. Chem. **51**, 188 (1938).
(94) BOESEKEN, J., AND HOEVERS, R.: Rec. trav. chim. **49**, 1165 (1930).
(95) BRAUN, J. v., AND MANZ, G.: Ber. **70B**, 1603 (1937).
(96) BROOKS, B., AND WILBERT, G.: J. Am. Chem. Soc. **63**, 870 (1941).
(97) BUTZ, L.: J. Am. Chem. Soc. **57**, 1314 (1935).
(98) BUTZ, L.: J. Am. Chem. Soc. **60**, 216 (1938).
(99) BUTZ, L., BUTZ, E., AND GADDIS, A.: J. Org. Chem. **5**, 171 (1940).
(100) BUTZ, L., GADDIS, A., BUTZ, E., AND DAVIS, R.: J. Org. Chem. **5**, 379 (1940).
(101) CAROTHERS, W., BERCHET, G., AND COLLINS, A.: J. Am. Chem. Soc. **54**, 4066 (1932).
(102) CAROTHERS, W., WILLIAMS, I., COLLINS, A., AND KIRBY, J.: J. Am. Chem. Soc. **53**, 4203 (1931).
(103) CHANG-KONG, C., AND CHIN-TSIEN, H.: Ber. **68B**, 876 (1935).
(104) CHAYANOV, N.: J. Gen. Chem. (U. S. S. R.) **8**, 460 (1938).
(105) CHAYANOV, N., AND GRISHIN, P.: Colloid J. (U. S. S. R.) **3**, 461 (1937).
(106) CHELINTZEV, W.: Bull. soc. chim. [5] **3**, 1035 (1936).
(107) CLAR, E.: Ber. **64B**, 1676 (1931).
(108) CLAR, E.: Ber. **64B**, 2194 (1931).
(109) CLAR, E.: Ber. **65B**, 503 (1932).
(110) CLAR, E.: Ber. **65B**, 846 (1932).
(111) CLAR, E.: Ber. **65B**, 1425 (1932).
(112) CLAR, E.: German patent 619,246 (September 26, 1935).
(113) CLAR, E.: Ber. **69B**, 1686 (1936).
(114) CLAR, E.: Ber. **72B**, 1817 (1939).
(115) CLAR, E.: Ber. **73B**, 351 (1940).
(116) CLAR, E.: Ber. **73B**, 409 (1940).
(117) CLAR, E., AND FURNARI, F.: Ber. **65B**, 1420 (1932).
(118) CLAR, E., AND GUZZI, A.: Ber. **65B**, 1521 (1932).
(119) CLAR, E., AND JOHN, F.: Ber. **63B**, 2967 (1930).
(120) CLAR, E., AND LOMBARDI, L.: Ber. **65B**, 1411 (1932).
(121) COFFMANN, D., AND CAROTHERS, W.: J. Am. Chem. Soc. **55**, 2040 (1933).
(122) COHEN, A.: J. Chem. Soc. **1935**, 429.
(123) COHEN, A., AND WARREN, F.: J. Chem. Soc. **1937**, 1315.
(124) COOK, J.: J. Chem. Soc. **1931**, 3273.
(125) COOK, J.: J. Chem. Soc. **1932**, 1472.
(126) COOK, J., AND LAWRENCE, C.: J. Chem. Soc. **1938**, 58.
(127) DALMER, O., WERDER, F. v., AND MOLL, T.: Z. physiol. Chem. **224**, 86 (1934).
(128) DAMSKY, A.: Ber. **20B**, 2966 (1887).
(129) DANE, E., AND EDER, K.: Ann. **539**, 207 (1939).
(130) DANE, E., HOESS, O., EDER, K., SCHMITT, J., AND SCHOEN, O.: Ann. **536**, 183 (1938).
(131) DANE, E., HOESS, O., BINDSEIL, A., AND SCHMITT, J.: Ann. **532**, 39 (1937).
(132) DANE, E., AND SCHMITT, J.: Ann. **536**, 196 (1938).
(133) DANE, E., AND SCHMITT, J.: Ann. **537**, 246 (1939).
(134) DANE, E., SCHMITT, J., AND RAUTENSTRAUCH, C.: Ann. **532**, 29 (1937).
(135) DIELS, O.: Ber. **69A**, 195 (1936).
(136) DIELS, O., AND ALDER, K.: Ann. **460**, 98 (1928).

(137) DIELS, O., AND ALDER, K.: Ber. **62B,** 2087 (1929).
(138) DIELS, O., AND ALDER, K.: Ber. **64B,** 2116 (1931).
(139) DIELS, O., AND ALDER, K.: U. S. patent 1,944,731 (January 23, 1934).
(140) DIELS, O., ALDER, K., FRIEDRICHSEN, W., KLARE, H., AND WINCKLER, H.: Ann. **505,** 103 (1933).
(141) DIELS, O., ALDER, K., FRIEDRICHSEN, W., PETERSEN, E., BRODERSEN, L., AND KECH, H.: Ann. **510,** 87 (1934).
(142) DIELS, O., ALDER, K., KASHIMOTO, T., FRIEDRICHSEN, W., ECKHARDT, W., AND KLARE, H.: Ann. **498,** 16 (1932).
(143) DIELS, O., ALDER, K., AND LUBBERT, W.: Ann. **490,** 277 (1931).
(144) DIELS, O., ALDER, K., LUBBERT, W., NAUJOKS, E., QUERBERITZ, F., ROEHL, K., AND SEGEBERG, H.: Ann. **470,** 62 (1929).
(145) DIELS, O., ALDER, K., AND MUELLER, K.: Ann. **490,** 257 (1931).
(146) DIELS, O., ALDER, K., AND NAUJOKS, E.: Ber. **62B,** 554 (1929).
(147) DIELS, O., ALDER, K., AND NIENBURG, H.: Ann. **490,** 236 (1931).
(148) DIELS, O., ALDER, K., NIENBURG, H., AND SCHMALBECK, O.: Ann. **490,** 243 (1931).
(149) DIELS, O., ALDER, K., AND PETERSEN, E.: Ann. **486,** 191 (1931).
(150) DIELS, O., ALDER, K., AND PETERSEN, E.: Ann. **486,** 202 (1931).
(151) DIELS, O., ALDER, K., PETERSEN, E., AND QUERBERITZ, F.: Ann. **478,** 137 (1930).
(152) DIELS, O., ALDER, K., AND PRIES, P.: Ber. **62B,** 2081 (1929).
(153) DIELS, O., ALDER, K., STEIN, G., PRIES, P., AND WINCKLER, H.: Ber. **62B,** 2337 (1929).
(154) DIELS, O., ALDER, K., AND WINCKLER, H.: Ann. **490,** 267 (1931).
(155) DIELS, O., ALDER, K., WINCKLER, H., AND PETERSEN, E.: Ann. **498,** 1 (1932).
(156) DIELS, O., ALDER, K., AND WINTER, D.: Ann. **486,** 211 (1931).
(157) DIELS, O., BLOM, J., AND KOLL, W.: Ann. **443,** 242 (1925).
(158) DIELS, O., AND FRIEDRICHSEN, W.: Ann. **513,** 145 (1934).
(159) DIELS, O., AND HARMS, J.: Ann. **525,** 73 (1936).
(160) DIELS, O., AND KASSEBART, R.: Ann. **530,** 51 (1937).
(161) DIELS, O., AND KECH, H.: Ann. **519,** 140 (1935).
(162) DIELS, O., KOCH, W., AND FROST, H.: Ber. **71B,** 1163 (1938).
(163) DIELS, O., AND KOENIG, H.: Ber. **71B,** 1179 (1938).
(164) DIELS, O., AND MEYER, R.: Ann. **513,** 129 (1934).
(165) DIELS, O., AND MOELLER, F.: Ann. **516,** 45 (1935).
(166) DIELS, O., AND OLSON, S.: J. prakt. Chem. **156,** 285 (1940).
(167) DIELS, O., AND PISTOR, H.: Ann. **530,** 87 (1937).
(168) DIELS, O., AND REESE, J.: Ann. **511,** 168 (1934).
(169) DIELS, O., AND REESE, J.: Ann. **519,** 147 (1935).
(170) DIELS, O., SCHMITT, S., AND WITTE, W.: Ber. **71B,** 1186 (1938).
(171) DIELS, O., AND SCHRUM, H.: Ann. **530,** 68 (1937).
(172) DIELS, O., AND THIELE, W.: Ber. **71B,** 1173 (1938).
(173) DIELS, O., AND THIELE, W.: Ann. **543,** 79 (1939).
(174) DIELS, O., AND THIELE, W.: J. prakt. Chem. **156,** 195 (1940).
(175) DIETERLE, H., SALOMON, A., AND NOSSECK, E.: Ber. **64B,** 2086 (1931).
(176) DILTHEY, W., HENKELS, S., AND SCHAEFER, A.: Ber. **71B,** 974 (1938).
(177) DILTHEY, W., AND HURTIG, G.: Ber. **67B,** 495 (1934).
(178) DILTHEY, W., AND HURTIG, G.: Ber. **67B,** 2004 (1934).
(179) DILTHEY, W., AND LEONHARD, M.: Ber. **73B,** 431 (1940).
(180) DILTHEY, W., AND QUINT, F.: J. prakt. Chem. [2] **128,** 139 (1930).
(181) DILTHEY, W., SCHOMMER, W., HOESCHEN, W., AND DIERICHS, H.: Ber. **68B,** 1159 (1935).
(182) DILTHEY, W., SCHOMMER, W., AND TRÖSKEN, O.: Ber. **66B,** 1627 (1933).
(183) DILTHEY, W., TER HORST, M., AND SCHAEFER, A.: J. prakt. Chem. [2] **148,** 53 (1937).
(184) DILTHEY, W., THEWALT, I., AND TRÖSKEN, O.: Ber. **67B,** 1959 (1934).

(185) DUFRAISSE, C., AND COMPAGNON, P.: Compt. rend. **207**, 585 (1938).
(186) DUFRAISSE, C., AND DANIEL, D.: Bull. soc. chim. [5] **4**, 2063 (1937).
(187) DUFRAISSE, C., AND PRIOU, R.: Bull. soc. chim. [5] **5**, 502 (1938).
(188) DUFRAISSE, C., AND PRIOU, R.: Bull. soc. chim. [5] **5**, 611 (1938).
(189) DUFRAISSE, C., VELLUZ, L., AND VELLUZ, L.: Bull. soc. chim. [5] **5**, 1073 (1938).
(190) DUPONT, G., AND DULOU, R.: Compt. rend. **202**, 1861 (1936).
(191) DUPONT, G., AND DULOU, R.: Atti X° congr. intern. chim. **3**, 123, 129 (1939).
(192) DUPONT, G., DULOU, R., DESREUX, V., AND PICOUX, R.: Bull. soc. chim. [5] **5**, 322 (1938).
(193) DUPONT, G., AND PACQUOT, C.: Compt. rend. **205**, 805 (1937).
(194) ECK, J., VAN PEURSEM, R., AND HOLLINGSWORTH, E.: J. Am. Chem. Soc. **61**, 171 (1939).
(195) EULER, H. v., AND JOSEPHSON, K.: Ber. **53B**, 822 (1920).
(196) FAIRCLOUGH, R., AND HINSHELWOOD, C.: J. Chem. Soc. **1938**, 236.
(197) FARMER, E.: Trans. Faraday Soc. **35**, 1034 (1939).
(198) FARMER, E., AND FAROOQ, M.: J. Chem. Soc. **1938**, 1925.
(199) FARMER, E., AND WARREN, F.: J. Chem. Soc. **1929**, 897.
(200) FARMER, E., AND WARREN, F.: J. Chem. Soc. **1931**, 3221.
(201) FAVORSKAYA, T.: J. Gen. Chem. (U. S. S. R.) **10**, 461 (1940).
(202) FAVORSKAYA, T., AND ZAKHAROVA, A.: J. Gen. Chem. (U. S. S. R.) **10**, 446 (1940).
(203) FIESER, L.: *Organic Chemistry*, edited by H. Gilman, Vol. I, pp. 52 ff. John Wiley and Sons, Inc., New York (1938).
(204) FIESER, L., AND BRADSHER, C.: J. Am. Chem. Soc. **61**, 417 (1939).
(205) FIESER, L., AND CAMPBELL, W.: J. Am. Chem. Soc. **60**, 159 (1938).
(206) FIESER, L., AND DAUDT, W.: J. Am. Chem. Soc. **63**, 782 (1941).
(207) FIESER, L., AND DUNN, J.: J. Am. Chem. Soc. **58**, 1054 (1936).
(208) FIESER, L., AND DUNN, J.: J. Am. Chem. Soc. **59**, 1016 (1937).
(209) FIESER, L., AND DUNN, J.: J. Am. Chem. Soc. **59**, 1021 (1937).
(210) FIESER, L., AND DUNN, J.: J. Am. Chem. Soc. **59**, 1024 (1937).
(211) FIESER, L., AND FIESER, M.: J. Am. Chem. Soc. **57**, 1679 (1935).
(212) FIESER, L., FIESER, M., AND HERSCHBERG, E.: Unpublished work; see reference 205.
(213) FIESER, L., FIESER, M., AND HERSCHBERG, E.: J. Am. Chem. Soc. **58**, 1463 (1936).
(214) FIESER, L., AND HERSCHBERG, E.: J. Am. Chem. Soc. **57**, 1508 (1935).
(215) FIESER, L., AND HERSCHBERG, E.: J. Am. Chem. Soc. **57**, 1681 (1935).
(216) FIESER, L., AND HERSCHBERG, E., J. Am. Chem. Soc. **57**, 2192 (1935).
(217) FIESER, L., AND HERSCHBERG, E.: J. Am. Chem. Soc. **58**, 2314 (1936).
(218) FIESER, L., AND HOLMES, H.: J. Am. Chem. Soc. **58**, 2319 (1936).
(219) FIESER, L., AND HOLMES, H.: J. Am. Chem. Soc. **60**, 2548 (1938).
(220) FIESER, L., AND PRICE, C.: J. Am. Chem. Soc. **58**, 1838 (1936).
(221) FIESER, L., AND SELIGMAN, A.: J. Am. Chem. Soc. **56**, 2690 (1934).
(222) FIESER, L., AND SELIGMAN, A.: Ber. **68B**, 1747 (1935).
(223) FIESER, L., AND WEBBER, T.: J. Am. Chem. Soc. **62**, 1360 (1940).
(224) FIESER, L., AND WIEGHAND, C.: J. Am. Chem. Soc. **62**, 153 (1940).
(225) FISCHER, H., HARTMANN, P., AND RIEDL, H.: Ann. **494**, 246 (1932).
(226) GASCOIGNE, R.: J. Proc. Roy. Soc. N. S. Wales **74**, 353 (1941).
(227) GOLDBERG, M., AND MÜLLER, P.: Helv. Chim. Acta **21**, 1699 (1938).
(228) GOODWAY, N., AND WEST, T.: J. Chem. Soc. **1938**, 2028.
(229) GOODWAY, N., AND WEST, T.: J. Chem. Soc. **1939**, 1853.
(230) GOODWAY, N., AND WEST, T.: J. Chem. Soc. **1940**, 702.
(231) GROSSE-OETRINGHAUS, H.: Petroleum Z. **35**, 567 (1939).
(232) GRUBER, E., AND ADAMS, R.: J. Am. Chem. Soc. **57**, 2555 (1935).
(233) HANCOX, N., AND JONES, T.: Univ. Queensland Papers, Dept. Chem. **1**, No. 14 (1939).
(234) HEILBRON, I., AND SIMPSON, J.: J. Chem. Soc. **1932**, 1708.

(235) HÖNIGMANN, H.: Ann. **508,** 89 (1934).
(236) HORIUTI, R., OTUKI, H., AND OKUDA, O.: Bull. Chem. Soc. Japan **14,** 501 (1939).
(237) HULTZSCH, K.: Angew. Chem. **51,** 920 (1938).
(238) HULTZSCH, K.: Ber. **72B,** 1173 (1939).
(239) I. G. FARBENINDUSTRIE A.-G.: British patent 303,389 (July 1, 1927).
(240) I. G. FARBENINDUSTRIE A.-G.: German patent 494,433 (May 8, 1928).
(241) I. G. FARBENINDUSTRIE A.-G.: British patent 320,375 (July 6, 1928).
(242) I. G. FARBENINDUSTRIE A.-G.: German patent 502,043 (July 6, 1928).
(243) I. G. FARBENINDUSTRIE A.-G.: German patent 500,160 (August 24, 1928).
(244) I. G. FARBENINDUSTRIE A.-G.: German patent 504,646 (September 13, 1928).
(245) I. G. FARBENINDUSTRIE A.-G.: British patent 327,128 (September 26, 1928).
(246) I. G. FARBENINDUSTRIE A.-G.: British patent 341,047 (October 15, 1928).
(247) I. G. FARBENINDUSTRIE A.-G.: French patent 673,825 (April 22, 1929).
(248) I. G. FARBENINDUSTRIE A.-G.: French patent 36,990 (May 30, 1929).
(249) I. G. FARBENINDUSTRIE A.-G.: French patent 37,337 (June 26, 1929).
(250) I. G. FARBENINDUSTRIE A.-G.: French patent 37,684 (July 27, 1929).
(251) I. G. FARBENINDUSTRIE A.-G.: German patent 597,325 (May 22, 1934).
(252) INHOFFEN, H.: Ann. **508,** 81 (1933).
(253) INHOFFEN, H.: Ber. **68B,** 973 (1935).
(254) JACOBSON, R., AND CAROTHERS, W.: J. Am. Chem. Soc. **55,** 1624 (1933).
(255) JOHNSON, J., JOBLING, W., AND BODAMER, G.: J. Am. Chem. Soc. **63,** 131 (1941).
(256) KARRER, P., CANAL, F., ZOHNER, K., AND WIDMER, R.: Helv. Chim. Acta **11,** 1062 (1928).
(257) KAUFMANN, H., AND BALTES, J.: Fette u. Seifen **43,** 93 (1936).
(258) KAUFMANN, H., AND BALTES, J.: Ber. **69B,** 2676 (1936).
(259) KAUFMANN, H., AND BALTES, J.: Ber. **69B,** 2679 (1936).
(260) KAUFMANN, H., BALTES, J., AND BÜTER, H.: Ber. **70B,** 903 (1937).
(261) KAUFMANN, H., BALTES, J., AND BÜTER, H.: Ber. **70B,** 2535 (1937).
(262) KAUFMANN, H., BALTES, J., AND JOSEPHS, F.: Ber. **70B,** 908 (1937).
(263) KAZANSKII, B., AND PLATE, A.: Ber. **68B,** 1259 (1935).
(264) KHAMBATA, B., AND WASSERMANN, A.: J. Chem. Soc. **1939,** 371.
(265) KHAMBATA, B., AND WASSERMANN, A.: J. Chem. Soc. **1939,** 375.
(266) KHARASCH, M., FINEMAN, M., AND MAYO, F.: J. Am. Chem. Soc. **61,** 2139 (1939).
(267) KHARASCH, M., NUDENBERG, W., AND STERNFELD, E.: J. Am. Chem. Soc. **62,** 2034 (1940).
(268) KHARASCH, M., AND STERNFELD, E.: J. Am. Chem. Soc. **61,** 2318 (1939).
(269) KÖGL, F., AND ERXLEBEN, H.: Ann. **479,** 11 (1930).
(270) KOHLER, E., AND KABLE, J.: J. Am. Chem. Soc. **57,** 917 (1935).
(271) KONDO, H., SUZUKI, H., AND TAKEDA, K.: J. Pharm. Soc. Japan **55,** 741 (1935).
(272) KUHN, R., AND DEUTSCH, A.: Ber. **65B,** 43 (1932).
(273) KUHN, R., AND WAGNER-JAUREGG, T.: Ber. **63B,** 2662 (1930).
(274) LAUER, W., AND MILLER, S.: J. Am. Chem. Soc. **57,** 520 (1935).
(275) LEBEDEV, S.: J. Russ. Phys.-Chem. Soc. **42,** 949 (1910).
(276) LEBEDEV, S., AND SKAVRONSKAYA, N.: J. Russ. Phys.-Chem. Soc. **43,** 1124 (1911).
(277) LEHMANN, E.: Ber. **69B,** 631 (1936).
(278) LEHMANN, E.: Ber. **71B,** 1869 (1938).
(279) LEHMANN, E.: Ber. **71B,** 1874 (1938).
(280) LEHMANN, E.: Ber. **73B,** 304 (1940).
(281) LEHMANN, E., AND PAASCHE, W.: Ber. **68B,** 1146 (1935).
(282) LETTRE, H.: Ann. **511,** 280 (1934).
(283) LEVINA, R., AND KIRYUSHOV, P.: J. Gen. Chem. (U. S. S. R.) **9,** 1834 (1940).
(284) LIPP, M., AND STEINBRINK, H.: J. prakt. Chem. **149,** 107 (1937).
(285) LITTMANN, E.: J. Am. Chem. Soc. **57,** 586 (1935).
(286) LITTMANN, E.: J. Am. Chem. Soc. **58,** 1316 (1936).

(287) LÖWENBEIN, A., AND ULICH, G.: Ber. **58B**, 2662 (1925).
(288) LOHAUS, H.: Ann. **516**, 295 (1935).
(289) LORA TAMAYO, M., AND AYESTARAN, D.: Anales soc. españ. fís. quím. **36**, 44 (1940).
(290) LÜTTRINGHAUS, A., NERESHEIMER, H., EICHHOLZ, W., BÖHMER, G., AND SCHNEIDER W.: U. S. patent 1,890,040 (December 6, 1932).
(291) MAMELI, E., PANCOTTO, A., AND CRESTANI, V.: Gazz. chim. ital. **67**, 669 (1937).
(292) MARTIN, S., GRUSE, W., AND LOWY, A.: Ind. Eng. Chem. **25**, 381 (1933).
(293) MEGGY, A., AND ROBINSON, R.: Nature **140**, 282 (1937).
(294) MÖHLAU, R., AND REDLICH, A.: Ber. **44B**, 3605 (1911).
(295) MORRELL, R., AND SAMUELS, H.: J. Chem. Soc. **1932**, 2251.
(296) MÜLLER, M.: Z. physiol. Chem. **233**, 223 (1935).
(297) NATSINSKAYA, N., AND PETROV, A.: J. Gen. Chem. (U. S. S. R.) **11**, 665 (1941).
(298) NEWMAN, M.: J. Am. Chem. Soc. **62**, 1683 (1940).
(299) ODDY, H.: J. Am. Chem. Soc. **45**, 2156 (1923).
(300) PETROV, V.: J. Chem. Soc. **1939**, 1000.
(301) PFEIFFER, P., AND BOTTLER, T.: Ber. **51B**, 1819 (1918).
(302) PIRSCH, J.: Ber. **67B**, 101 (1934).
(303) POLYAKOVA, N.: Coke and Chem. (U. S. S. R.) No. 2-3, 75 (1938).
(304) POWERS, P.: Ind. Eng. Chem., News Ed. **19**, 750 (1941).
(305) PRATESI, P.: Gazz. chim. ital. **66**, 215 (1936).
(306) PUMMERER, R., FIESSELMANN, H., AND MÜLLER, O.: Ann. **544**, 206 (1940).
(307) RAUDNITZ, H., AND STEIN, W.: Ber. **68B**, 1479 (1935).
(308) RINCKES, I.: Rec. trav. chim. **50**, 1127 (1931).
(309) ROBEY, R., MORRELL, C., AND WIESE, H.: J. Am. Chem. Soc. **63**, 627 (1941).
(310) ROBINSON, R., WALKER, J., AND TODD, A.: J. Chem. Soc. **1935**, 1530.
(311) ROMBURGH, P. v., AND ROMBURGH, G. v.: Proc. Acad. Sci. Amsterdam **34**, 224 (1931).
(312) RUDAKOV, G.: J. Gen. Chem. (U. S. S. R.) **10**, 1673 (1940).
(313) RUZICKA, L.: Helv. Chim. Acta **19**, 419 (1936).
(314) RUZICKA, L., ANKERSMIT, P., AND FRANK, B.: Helv. Chim. Acta **15**, 1289 (1932).
(315) RUZICKA, L., AND BOSCH, W.: Helv. Chim. Acta **14**, 1336 (1931).
(316) RUZICKA, L., AND KAUFMANN, S.: Helv. Chim. Acta **23**, 1346 (1940).
(317) RUZICKA, L., AND LALANDE, W., JR.: Helv. Chim. Acta **23**, 1357 (1940).
(318) RUZICKA, L., AND ZIMMERMANN, W.: Helv. Chim. Acta **18**, 219 (1935).
(319) RUZICKA, L., ZIMMERMANN, W., AND HUBER, K.: Helv. Chim. Acta **19**, 348 (1936).
(320) RYDON, H.: Chemistry & Industry **57**, 123 (1938).
(321) SALFELD, J.: Ber. **73B**, 376 (1940).
(322) SANDERMANN, W.: Ber. **71B**, 648 (1938).
(323) SANDERMANN, W.: Seifensieder-Ztg. **65**, 553 (1938).
(324) SANDERMANN, W.: Ber. **74B**, 154 (1941).
(325) SAYTZEW, M., AND SAYTZEW, A.: Ann. **185**, 151 (1877).
(326) SCHOENBERG, A., AND ISMAIL, A.: Nature **144**, 910 (1939).
(327) SCHOENBERG, A., AND ISMAIL, A.: J. Chem. Soc. **1940**, 1374.
(328) SCHOEPF, C., GOTTBERG, K. v., AND PETRI, W.: Ann. **536**, 216 (1938).
(329) SEMMLER, F., AND JONAS, K.: Ber. **46B**, 1566 (1913).
(330) SHERLIN, S., BERLIN, A., SEREBRENNIKOVA, T., AND RABINOVITCH, F.: J. Gen. Chem. (U. S. S. R.) **8**, 7 (1938).
(331) SHORYGIN, P., AND GUSEVA, A.: J. Gen. Chem. (U. S. S. R.) **6**, 1569 (1936).
(332) SLOBODIN, Y.: J. Gen. Chem. (U. S. S. R.) **5**, 1415 (1935).
(333) SLOBODIN, Y.: J. Gen. Chem. (U. S. S. R.) **6**, 129 (1936).
(334) SLOBODIN, Y., AND KRASNOBAEVA, P.: J. Gen. Chem. (U. S. S. R.) **8**, 738 (1938).
(335) SLOBODSKOI, A., AND KHMELEVSKII, V.: J. Gen. Chem. (U. S. S. R.) **10**, 1199 (1940).
(336) SMITH, L., AGRE, C., LEEKLEY, R., AND PRICHARD, W.: J. Am. Chem. Soc. **61**, 7 (1938).
(337) STAUDINGER, H.: *Die Ketene*, pp. 11–13, 23, 59. F. Enke, Stuttgart (1912).

(338) STAVELY, H., AND BERGMANN, W.: J. Org. Chem. **1**, 567 (1937).
(339) STAVELY, H., AND BERGMANN, W.: J. Org. Chem. **1**, 575 (1937).
(340) STRAUS, F., KUHNEL, R., AND HAENSEL, R.: Ber. **66B**, 1847 (1933).
(341) THIELE, J., BALHORN, H., WITH ALBRECHT, W.: Ann. **348**, 1 (1906).
(342) TISCHCHENKO, V., AND BOGOMOLOV, A.: Khim. Referat. Zhur. **1939**, No. 7, 26.
(343) TROPSCH, H., AND MATTOX, W.: Ind. Eng. Chem., Anal. Ed. **6**, 104 (1934).
(344) WAGNER-JAUREGG, T.: Ber. **63B**, 3213 (1930).
(345) WAGNER-JAUREGG, T.: Ann. **488**, 176 (1931).
(346) WAGNER-JAUREGG, T.: Ann. **491**, 1 (1931).
(347) WAGNER-JAUREGG, T., AND HELMERT, E.: Ber. **71B**, 2535 (1938).
(348) WAGNER-JAUREGG, T., AND WERNER, G.: Z. physiol. Chem. **213**, 119 (1932).
(349) WALLACH, O.: Ann. **227**, 295 (1895).
(350) WASSERMANN, A.: J. Chem. Soc. **1935**, 1511.
(351) WASSERMANN, A.: J. Chem. Soc. **1936**, 432.
(352) WEIDLICH, H.: Ber. **71B**, 1203 (1938).
(353) WEISS, R., ABELES, A., AND KNAPP, E.: Monatsh. **61**, 162 (1932).
(354) WEISS, R., AND BELLER, A.: Monatsh. **61**, 143 (1932).
(355) WEISS, R., AND KOLTES, J.: Monatsh. **65**, 351 (1935).
(356) WEISS, R., AND MAYER, F.: Monatsh. **71**, 6 (1937).
(357) WEST, T.: J. Chem. Soc. **1940**, 1162.
(358) WICHTERLE, O.: Collection Czechoslovak. Chem. Commun. **10**, 497 (1938).
(359) WIENHAUS, H., AND SANDERMANN, W.: Ber. **69B**, 2202 (1936).
(360) WINDAUS, A., DITHMAR, K., MARKE, H., AND SUCKFÜLL, F.: Ann. **488**, 91 (1931).
(361) WINDAUS, A., GAEDE, J., KOESER, J., AND STEIN, G.: Ann. **483**, 17 (1930).
(362) WINDAUS, A., AND INHOFFEN, H.: Ann. **510**, 260 (1934).
(363) WINDAUS, A., INHOFFEN, H., AND REICHEL, S. v.: Ann. **510**, 248 (1934).
(364) WINDAUS, A., AND LANGER, R.: Ann. **508**, 105 (1934).
(365) WINDAUS, A., LINSERT, O., LÜTTRINGHAUS, A., AND WEIDLICH, G.: Ann. **492**, 226 (1932).
(366) WINDAUS, A., AND LÜTTRINGHAUS, A.: Ber. **64B**, 850 (1931).
(367) WINDAUS, A., LÜTTRINGHAUS, A., AND DEPPE, M.: Ann. **489**, 252 (1931).
(368) WINDAUS, A., AND THIELE, W.: Ann. **521**, 160 (1935).
(369) WINDAUS, A., WERDER, V., AND LÜTTRINGHAUS, A.: Ann. **499**, 188 (1932).
(370) WINDAUS, A., AND ZÜHLSDORF, G.: Ann. **536**, 204 (1938).
(371) WOLFE, W.: U. S. patent 2,217,632 (October 8, 1940).
(372) WOLFE, W.: U. S. patent 2,222,357 (November 19, 1940).
(373) WOODWARD, R.: J. Am. Chem. Soc. **62**, 1478 (1940).
(374) ZIEGLER, K., AND SCHNELL, B.: Ann. **445**, 266 (1935).
(375) ZINCKE, A., NOCULAK, U., SKRABAL, R., AND TROGER, H.: Ber. **73B**, 1187 (1940).
(376) ZINCKE, T.: Ann. **367**, 1 (1909).
(377) ZINCKE, T., AND GUENTHER, H.: Ann. **272**, 243 (1893).
(378) ZINCKE, T., AND PFAFFENDORF, W.: Ann. **394**, 7 (1912).

References added after original compilation

(379) ALBRECHT, W.: Ann. **348**, 31 (1906).
(380) ALDER, K., OFFERMANNS, H., AND RUEDEN, E.: Ber. **74B**, 905 (1941).
(381) ALDER, K., OFFERMANNS, H., AND RUEDEN, E.: Ber. **74B**, 926 (1941).
(382) ALDER, K., AND RICKERT, H.: U. S. patent 2,264,354 (December 2, 1941).
(383) ALDER, K., AND RUEDEN, E.: Ber. **74B**, 920 (1941).
(384) ALEKSEEVA, E.: J. Gen. Chem. (U. S. S. R.) **11**, 353 (1941).
(385) ALEKSEEVA, E., AND BELITSKAYA, R.: J. Gen. Chem. (U. S. S. R.) **11**, 358 (1941).
(386) ALLEN, C., AND BELL, A.: J. Am. Chem. Soc. **64**, 1253 (1942).
(387) ALLEN, C., AND VAN ALLAN, J.: J. Am. Chem. Soc. **64**, 1260 (1942).
(388) ARBUZOV, B.: J. Gen. Chem. (U. S. S. R.) **6**, 297 (1936).

(389) ARNOLD, R.: J. Am. Chem. Soc. **61,** 1405 (1939).
(390) BACHMAN, G., AND GOEBEL, C.: J. Am. Chem. Soc. **64,** 787 (1942).
(391) BACHMANN, W., AND CHEMERDA, J.: J. Am. Chem. Soc. **60,** 1023 (1938).
(392) BADISCHE ANILIN UND SODA FABRIK: German patent 252,499.
(393) BERGMANN, F.: J. Am. Chem. Soc. **64,** 69 (1942).
(394) BERGMANN, F.: J. Am. Chem. Soc. **64,** 176 (1942).
(395) BEYER, H., AND FRITSCH, H.: Ber. **74B,** 494 (1941).
(396) BRADLEY, T., AND JOHNSTON, W.: Ind. Eng. Chem. **33,** 86 (1941).
(397) BUTZ, L.: J. Am. Chem. Soc. **64,** 1978 (1942).
(398) BUTZ, L., AND JOSHEL, L.: J. Am. Chem. Soc. **63,** 3344 (1941).
(399) BUTZ, L., AND JOSHEL, L.: J. Am. Chem. Soc. **64,** 1311 (1942).
(400) CLAPP, D.: J. Am. Chem. Soc. **61,** 2733 (1939).
(401) DERMER, O., AND KING, J.: J. Am. Chem. Soc. **63,** 3232 (1941).
(402) DYKSTRA, H.: J. Am. Chem. Soc. **57,** 2255 (1935).
(403) DYKSTRA, H.: J. Am. Chem. Soc. **58,** 1747 (1936).
(404) DYKSTRA, H.: U. S. patent 2,119,531 (June 7, 1938).
(405) ECK, J., AND HOLLINGSWORTH, E.: J. Am. Chem. Soc. **64,** 140 (1942).
(406) FIESER, L., AND NOVELLO, F.: J. Am. Chem. Soc. **64,** 802 (1942).
(407) GOLDBLATT, L., AND PALKIN, S.: J. Am. Chem. Soc. **63,** 3517 (1941).
(408) GRUMMITT, O., KLOPPER, R., AND BLENKHORN, C.: J. Am. Chem. Soc. **64,** 604 (1942).
(409) HUDSON, B., AND ROBINSON, R.: J. Chem. Soc. **1941,** 715.
(410) HUGGINS, A., AND YOKLEY, O.: J. Am. Chem. Soc. **64,** 1160 (1942).
(411) JOSHEL, L., AND BUTZ,[3] L.: J. Am. Chem. Soc. **63,** 3350 (1941).
(412) JOSHEL, L., BUTZ, L., AND FELDMAN, J.: J. Am. Chem. Soc. **63,** 3348 (1941).
(413) KHARASCH, M., AND TAWNEY, P.: J. Am. Chem. Soc. **63,** 2308 (1941).
(414) KISTIAKOWSKY, G., RUHOFF, J., SMITH, H., AND VAUGHAN, W.: J. Am. Chem. Soc. **58,** 146 (1936).
(415) MCELVAIN, S., AND COHEN, H.: J. Am. Chem. Soc. **64,** 260 (1942).
(416) MANNICH, C.: Ber. **74B,** 557 (1941).
(417) MARSCHALK, C.: Bull. soc. chim. **8,** 354 (1941).
(418) OKUDA, O.: J. Chem. Soc. Japan **61,** 161 (1940).
(419) PETROV, A.: J. Gen. Chem. (U. S. S. R.) **11,** 661 (1941).
(420) PETROV, V.: J. Gen. Chem. (U. S. S. R.) **11,** 309 (1941).
(421) POLYAKOVA, I.: Org. Chem. Ind. (U. S. S. R.) **7,** 305 (1940).
(422) SCHMITT, J.: Ann. **547,** 103 (1941).
(423) SNYDER, H., HASBROUCK, R., AND RICHARDSON, J.: J. Am. Chem. Soc. **61,** 3558 (1939).
(424) SNYDER, H., AND ROBINSON, J.: J. Am. Chem. Soc. **63,** 3279 (1941).
(425) WEIZMAN, C., BERGMANN, E., AND HASKELBERG, L.: J. Chem. Soc. **1939,** 391.
(426) WEST, T.: J. Chem. Soc. **1941,** 140.
(427) ZELINSKII, N., MIKHAILOV, B., AND ARBUZOV, Y.: J. Gen. Chem. (U. S. S. R.) **4,** 856 (1934).