TABLE 7

The additions of maleic anhydride to dienic acids and their derivatives

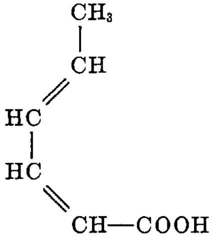
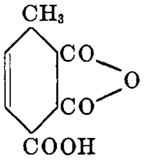
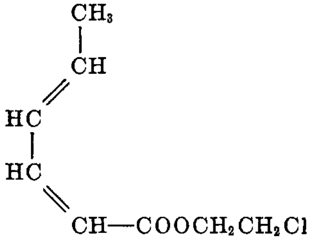
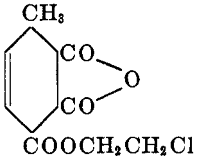
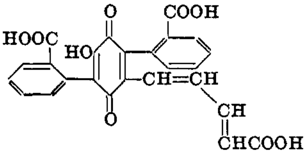
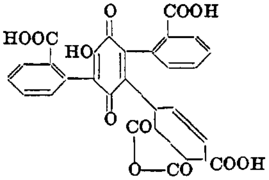
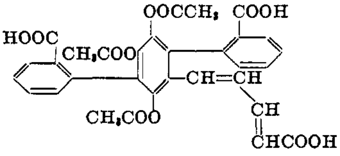
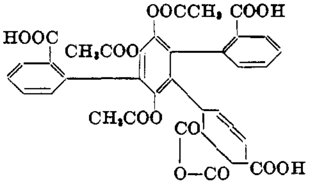
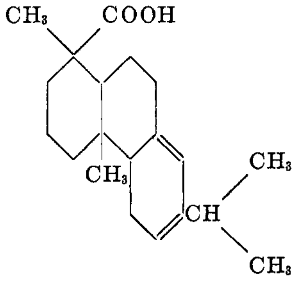
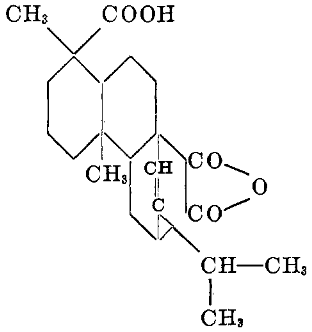
DIENE	DIENE STRUCTURE	PRODUCT STRUCTURE	REFERENCE
Sorbic acid......			(199)
β-Chloroethyl sorbate			(347)
Muscarufin			(269)
Triacetylleuco-muscarufin			(269)
l-Pimaric acid ...			(69, 205, 317, 324, 359)

TABLE 7—*Continued*

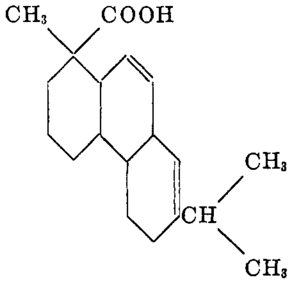
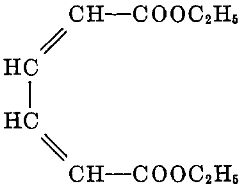
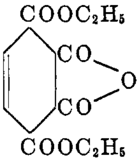
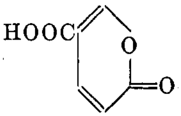
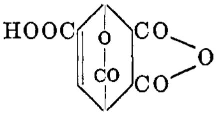
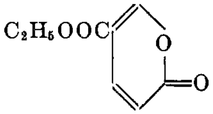
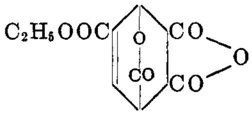
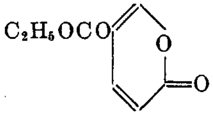
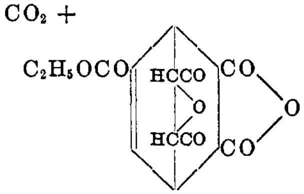
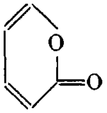
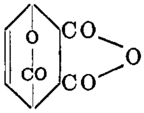
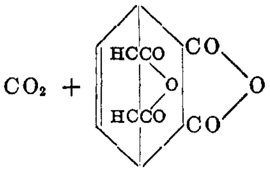
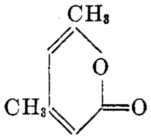
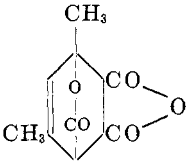
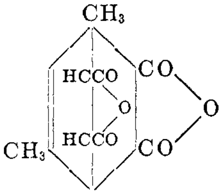
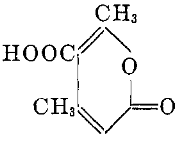
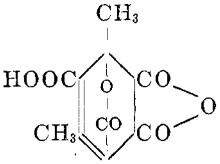
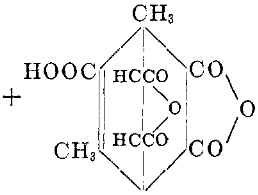
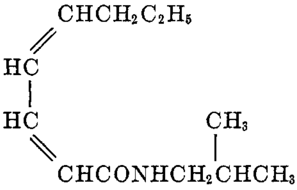
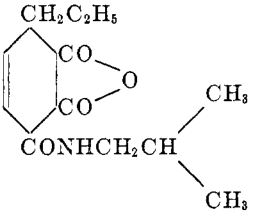
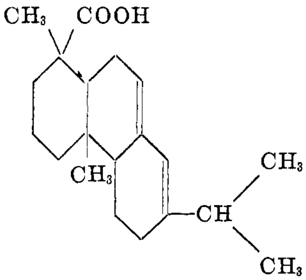
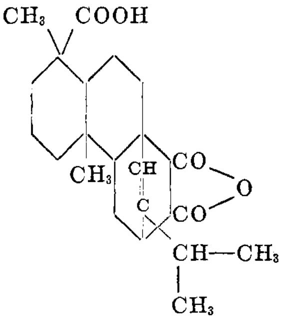
DIENE	DIENE STRUCTURE	PRODUCT STRUCTURE	REFERENCE
d-Pimaric acid...		Polymeric product	(314)
Ethyl *trans-trans*-muconate.			(199)
Cumalinic acid ..			(145)
Cumalinic ester (at 110°C.)			(145)
Cumalinic ester (at 138–140°C.).			(145)
Cumalin.........		 or 	(145)

TABLE 7—*Continued*

DIENE	DIENE STRUCTURE	PRODUCT STRUCTURE	REFERENCE
Dimethylcumalin		 or CO_2 + 	(145)
Isodehydracetic acid		 or CO_2 + 	(145)
Spilanthole			(64)
Abietic acid*			(55, 314)

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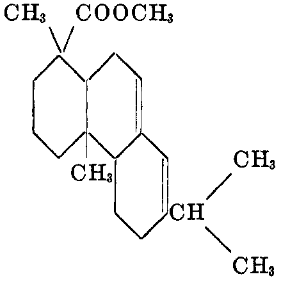
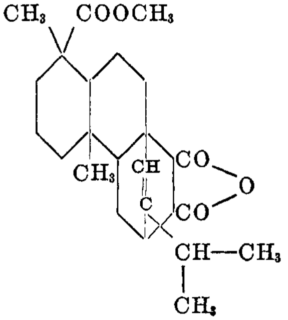
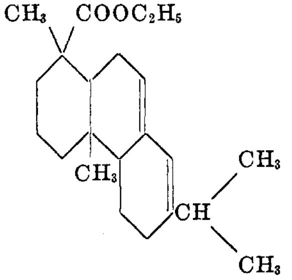
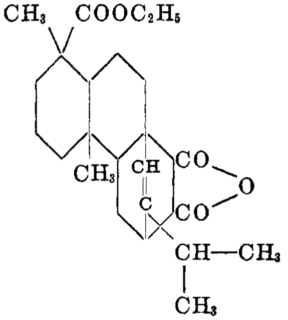
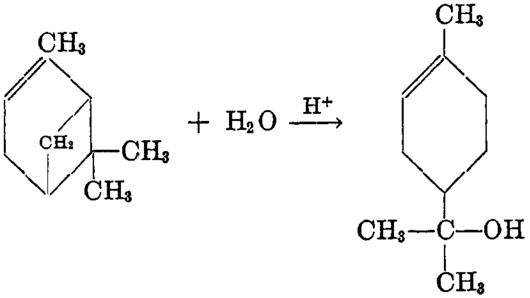
* Fieser's structure for abietic acid. Its adduct is identical with that obtained from *l*-pimaric acid.

TABLE 7—*Concluded*

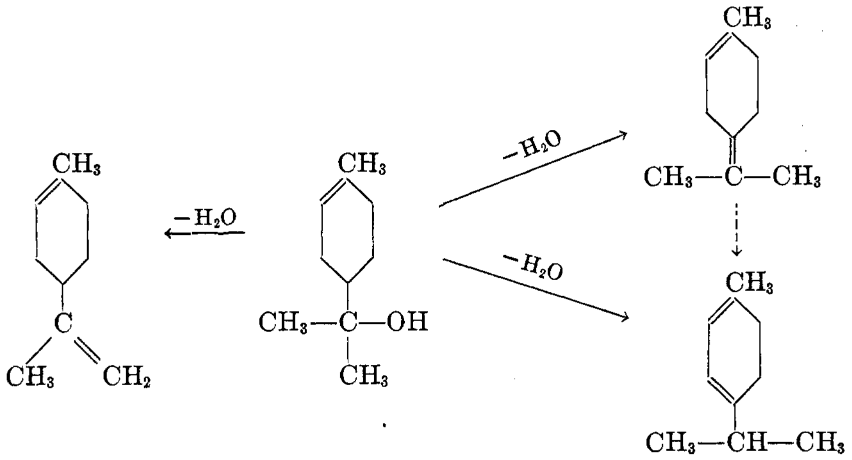
DIENE	DIENE STRUCTURE	PRODUCT STRUCTURE	REFERENCE
Methyl abietate.			(314)
Ethyl abietate...			(314)

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):

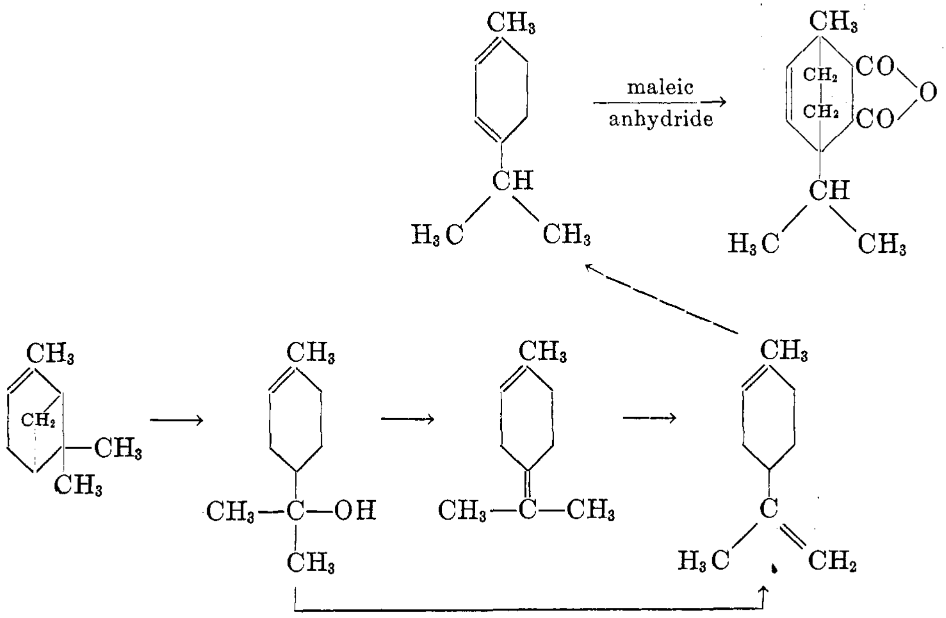


The tertiary alcohol can lose water and form *dl*-limonene or terpinolene. Alder and Rickert (15) obtained mostly 1,3-menthadiene by direct degradation:



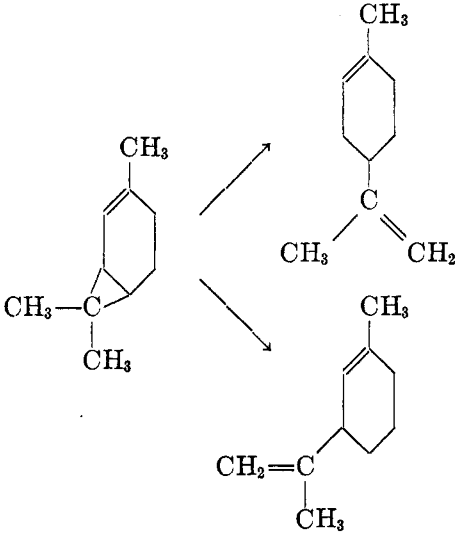
Semicyclic double bonds such as exist in terpinolene wander into the ring under the influence of acids. In this manner terpinolene gives terpinene (1,3-*p*-menthadiene) very readily with dilute acid. Dilute acids also transform terpineol into terpinolene, *dl*-limonene, or 1,3-*p*-menthadiene, depending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

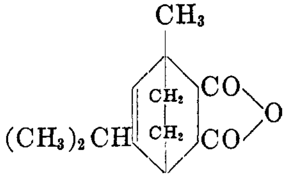


Since limonene and terpinolene are intermediates in the transformation of α-pinene to 1,3-*p*-menthadiene, their reactions with maleic acid are obvious. Support for this mechanism is furnished by the observation (226) that terpinolene and γ-terpinene do not add maleic anhydride at room temperature.

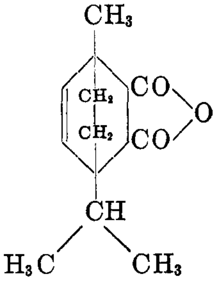
3-Carene (4-carene) is easily isomerized by dilute acids to a mixture of *dl*-limonene and sylvestrene:



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



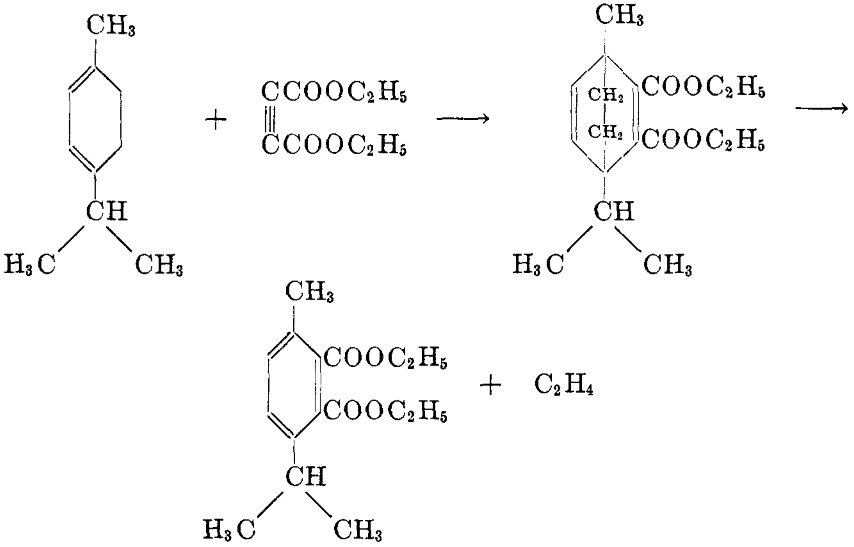
II

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.

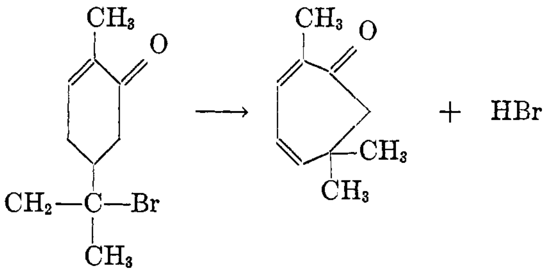
Arbuzov (56, 57; see also 388) passed α-pinene over copper chromite. At 300°C., a mixture of 80 per cent α-pinene and 20 per cent alloöcimene was obtained, while at 375°C. the composition was 23 per cent α-pinene, 31 per cent alloöcimene, and 12 per cent *dl*-limonene, whilst at 400–410°C., the composition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



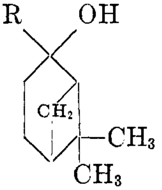
A second terpene was produced in addition to α-terpinene when terpineol was dehydrated (15). This contained conjugated double bonds, for it added acetylenedicarboxylic ester easily. This adduct did not decompose on distillation; hence the terpene is not a cyclohexadiene derivative. Alder and Rickert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



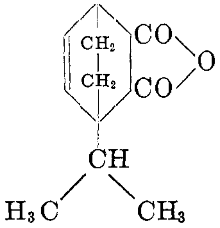
The cycloheptadienone is eucarvone. In accordance with this reaction, they believe their terpene to be eucarvene. Prior to this study, it had been generally believed that "terpinene" derived from terpineol was a mixture of 1,3- and 1,4-*p*-menthadienes.

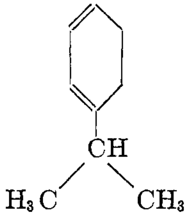
Acrolein has been reported (342) to "add" to *dl*-limonene to give "a liquid which gives *dl*-limonene on distillation at atmospheric pressure."

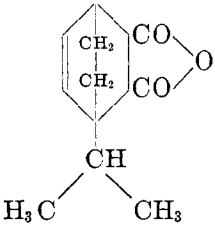
A few more instances are available of diene reactions of terpinoid bodies which do not contain conjugated double bonds (284). These terpinoid bodies are interesting in that they contain no unsaturated linkages whatever, yet give diene reactions. These are the so-called nopinols,



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

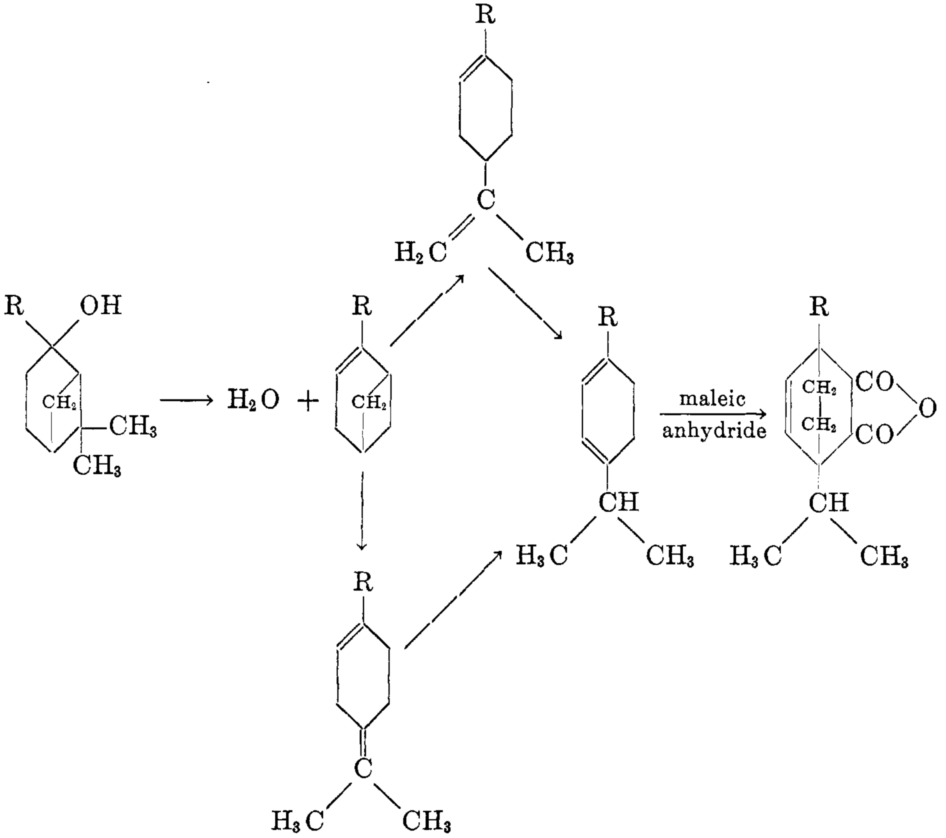

I


II

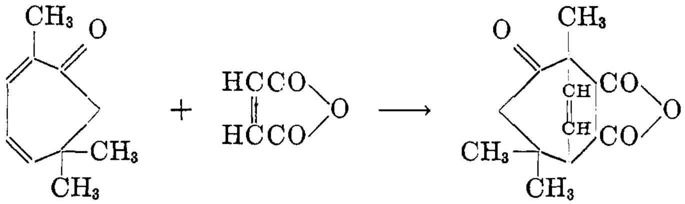

III

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

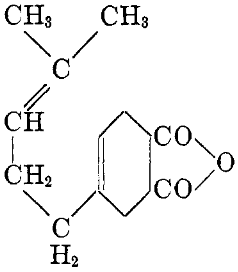
R is an alkyl or aryl group, the material is a tertiary alcohol. Evidently one of the first steps in the process of addition is the elimination of water to form norpinene, pinene, or a related compound dependent on the identity of R. It will be recalled that secondary alcohols are dehydrated less readily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

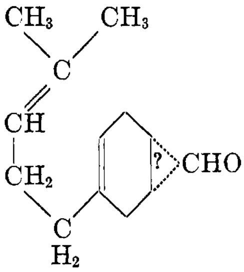


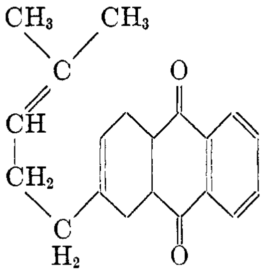
von Baeyer's eucarvone (70) has been observed to add maleic anhydride (33, 353) and acetylenedicarboxylic ester (15) (see page 404).



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

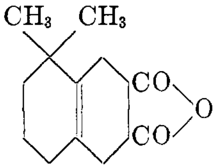

IV

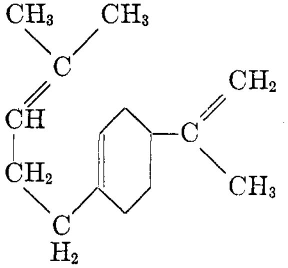

V

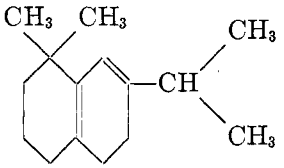

VI

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).

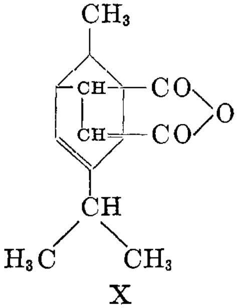
Isoprene will add to myrcene (315, 329) to give the so-called cycloisoprenemyrcene (VIII). Semmler and Jonas (329) observed this reaction as early as 1913 and found that *dl*-limonene is also produced (by dimerization of the isoprene). VIII cyclizes with formic acid (315) to give IX, the double-bond wandering being quite likely because of the acid conditions of the cyclization reaction. Dehydrogenation of the cyclizate gives eudalene.


VII


VIII

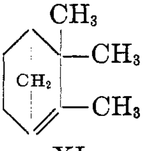

IX

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.

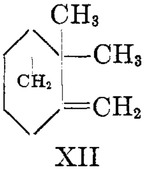

X

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.

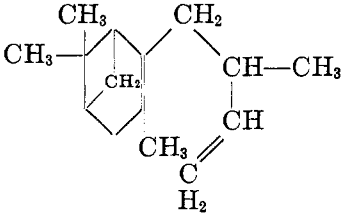


XI

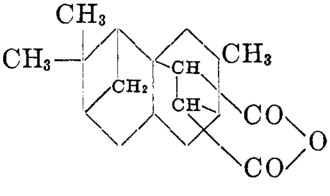


XII

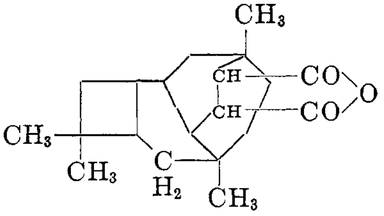
Ruzicka and Zimmermann (318) observed that the mixture of sesquiterpenes known as caryophyllene reacts with maleic anhydride to give a 70 per cent yield of adduct. At the time (1935) the formula of the main constituent of caryophyllene was given as XIII. In order to account for the formation of an adduct 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

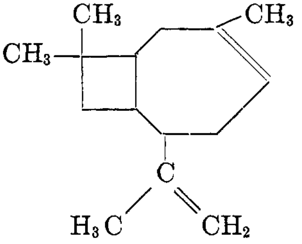


XIV

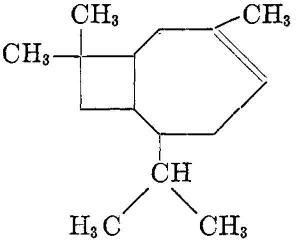


XV

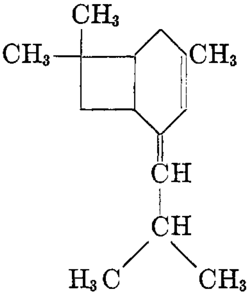
319) appeared to state the case no more satisfactorily. In 1938, Rydon (320) proposed that the main constituent of caryophyllene is a cycloheptene derivative (XVI), and that the maleic anhydride adduct is formed from a conjugated isomer (XVII). Since an alternative isomer (XVIII) is a *trans*-butadienoidal 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



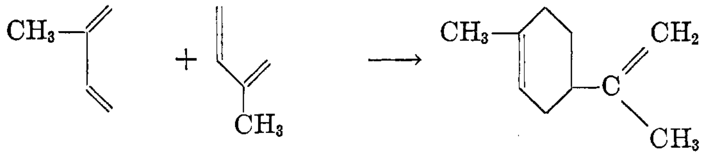
XVIII

IX. DIMERIZATION

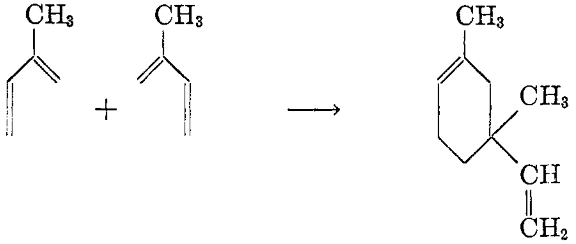
A number of dimerization reactions of the type which may be represented by the diene synthesis had been discovered half a century or more ago. Representative of those observed around the beginning of the twentieth century is that of Wallach (349) who, in the year 1895, synthesized *dl*-limonene by dimerization 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):

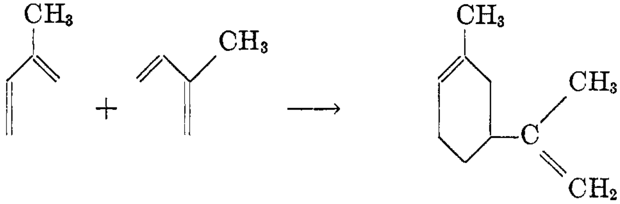
(A)



(B)

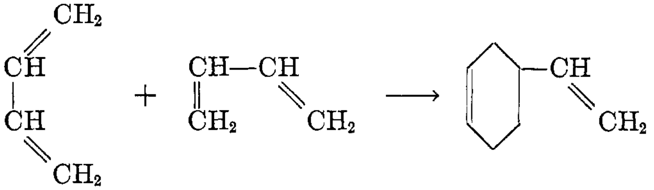


(C)

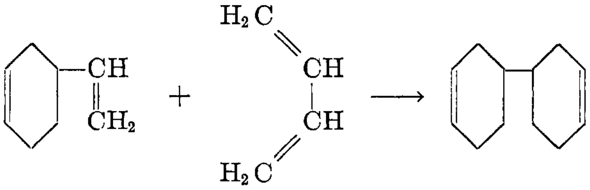


Absence of products resulting from reaction B is in harmony with the general observations concerning optional additions of dienophiles. These are explained in greater detail on page 329.

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:

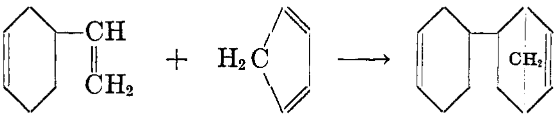


The product (vinylcyclohexene-3 or 4-vinylcyclohexene) does not add dienophiles, and therefore any proposed structure containing a conjugated system is unlikely. Dehydrogenation gives ethylbenzene; styrene may also be formed. Vinylcyclohexene-3 can add butadiene at elevated temperatures under antioxidant 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.

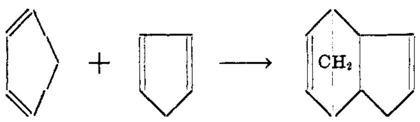
Vinylcyclohexene-3 will add other dienes as well as butadiene. Cyclopentadiene is added to give 1,2,3,6,1′,2′,5′,6′-octahydro-3,6-endomethylenebiphenyl:



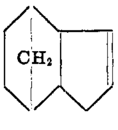
A considerable amount of α-tricyclopentadiene was formed in the above diene synthesis. The term "α-tricyclopentadiene" is a misnomer; it and similar names should be construed as meaning the trimer of cyclopentadiene.

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

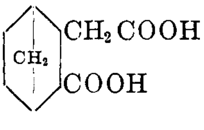
Pirsch (302) discusses the various possible structures of the dimer of cyclopentadiene. This dimer is often referred to as dicyclopentadiene, especially in the older literature. Alder and Stein published a series of papers dealing with the proof of structure of this and other polymers, making a number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



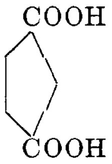
The degradation of the dimer to cyclopentane-1,3-dicarboxylic acid was accomplished in the following sequence of reactions: Partial hydrogenation of the dimer gives I, oxidation of which gives 3,6-endomethylenehexahydrohomophthalic acid (II). Further oxidation of II gives cyclopentanedicarboxylic acid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



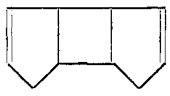
I



II

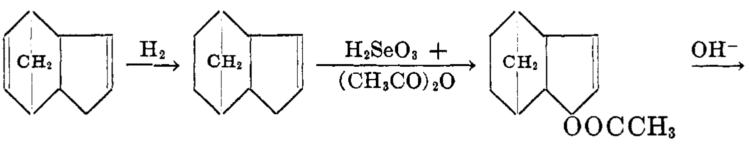


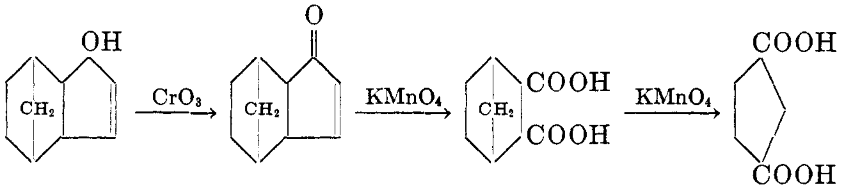
III



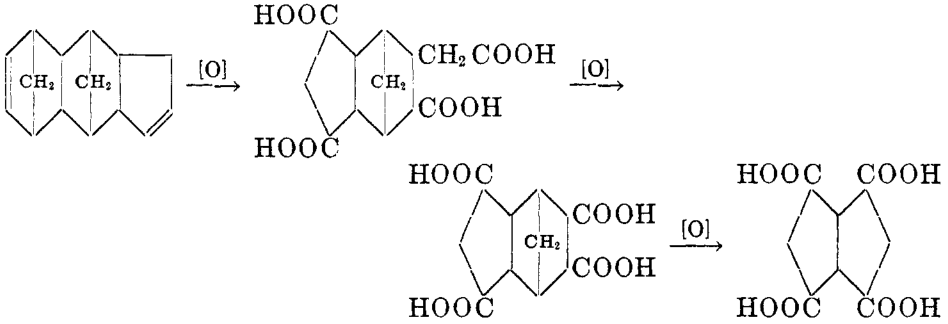
IV

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



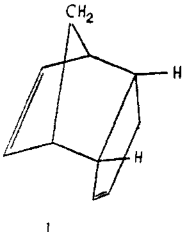


The reaction of phenyl azide with the double bond of the bicycloheptene ring appears to be rather specific, and was much used by Alder and Stein as a test for the presence of this ring in cyclopentadiene polymers. The test is not limited to detecting this ring in the polymers of cyclopentadiene, for 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:

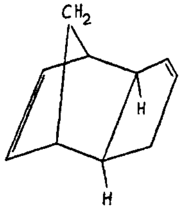


The double bond of the bicycloheptene ring is much more reactive than the other double bond of the dimer. Selective hydrogenation of this bond is accomplished with ease, and nitrosyl chloride adds to this bond rather than to the other. It would seem logical, therefore, that when the dimer adds another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



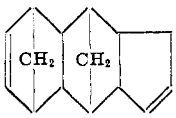
endo



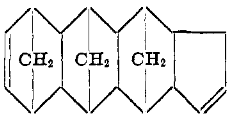
exo

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).

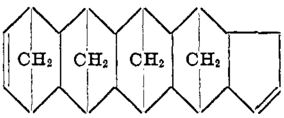
Since the trimer, tetramer, pentamer, etc., of cyclopentadiene are all formed by a series of diene syntheses involving the active double bond of the bicycloheptene ring as the "carbonylenic" double bond (though no carbonyl group is present, this term is used to denote the dienophilic double bond), the structures of these compounds are V, VI, and VII, respectively, in which all the endo-methylene 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

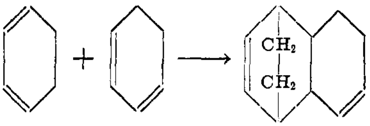


VI

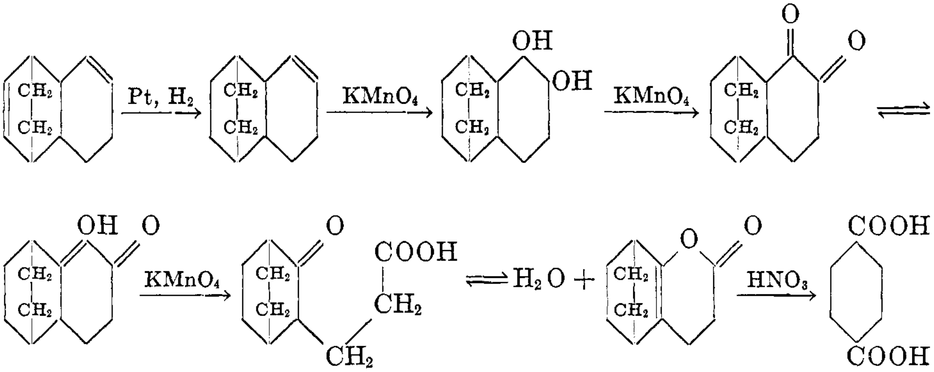


VII

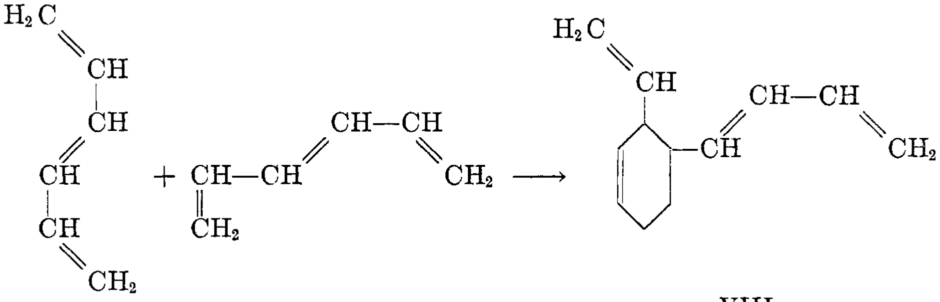
Cyclohexadiene dimerizes in a manner similar to that of cyclopentadiene (22, 46). When considered as a diene synthesis, the product would be of the structure indicated by the reaction



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:

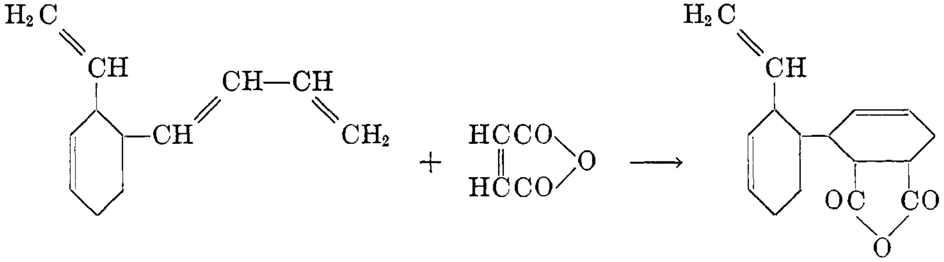


Kharasch and Sternfeld (268) prepared 1,3,5-hexatriene by the reaction of allyl chloride with a solution of sodium amide in liquid ammonia. This was found to dimerize to give VIII, the structure of which was proved.

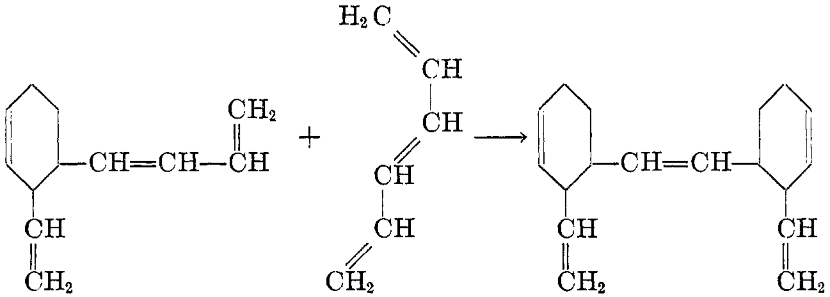


VIII

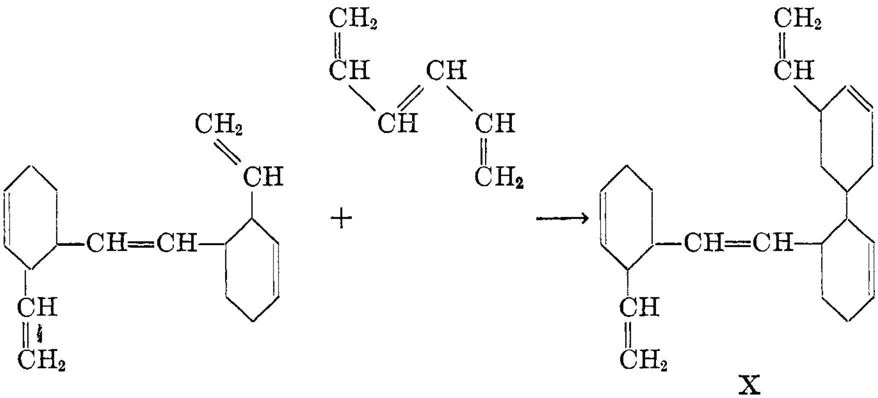
Since the dimer possesses a pair of conjugated double bonds, it adds maleic anhydride:



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

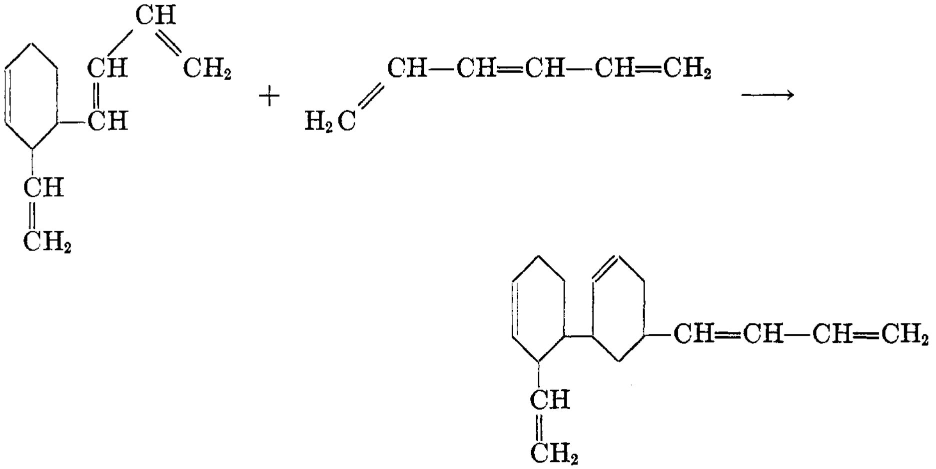


IX

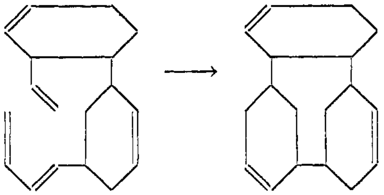


X

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:

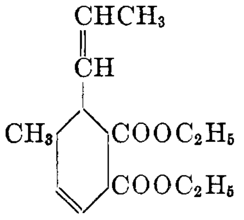


This trimer might undergo self-stabilization through an intramolecular diene reaction:



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.

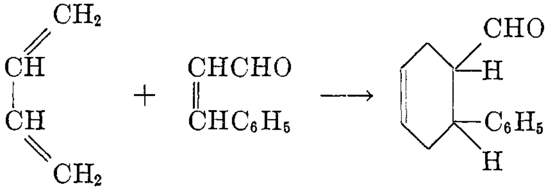


XI

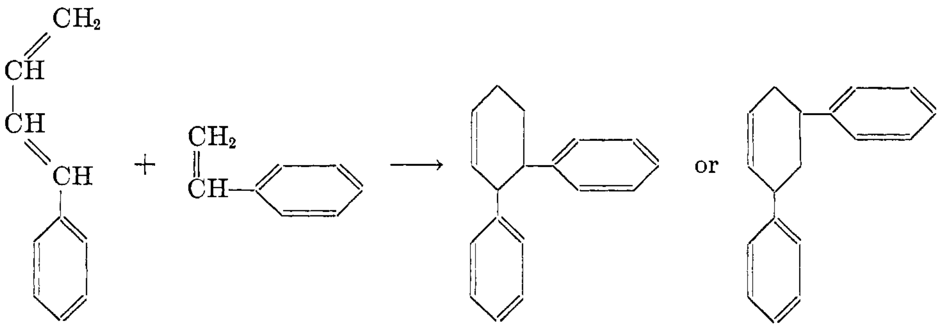
1-Phenylbutadiene (82) appears to dimerize abnormally, since the dimer is not a cyclohexene derivative but is 1-(β-styryl)-2-benzyl-3-cyclopentene. This structure was proved by oxidation of the compound to benzoic and α-benzyltricarballylic acids. Farmer (197) states that, with the exception of 1-phenylbutadiene,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



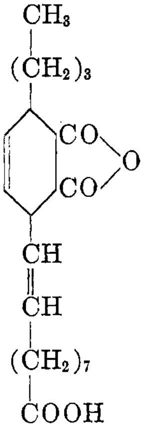
1-Phenylbutadiene and styrene should yield terphenyl derivatives:



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).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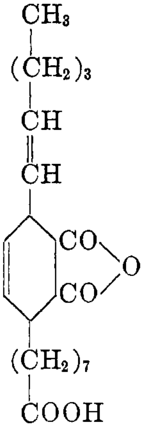
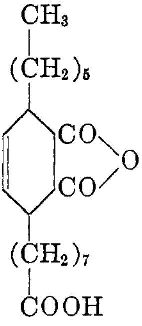

II

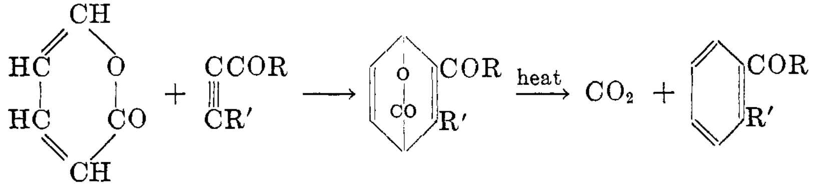

III

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.

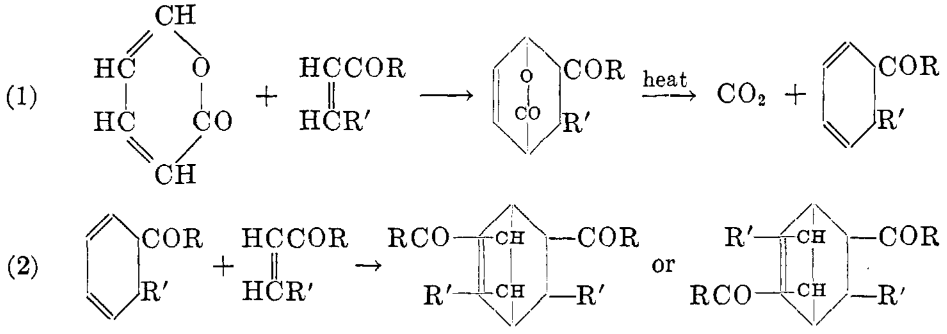
Sorbic acid esters add dienophiles. Ethyl sorbate adds benzoylethylene (47) to give 1,2,5,6-tetrahydro-3-methylbenzophenone-6-carboxylic ester, the structure of which was proved. β-Chloroethyl sorbate adds acryloyl chloride (347) to give 1,2,3,4-tetrahydro-4-methylisophthaloyl dichloride, the ester group 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:

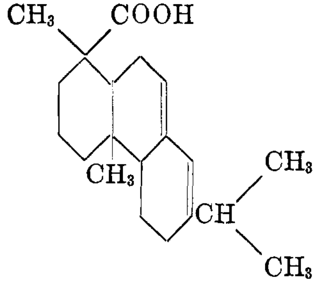


(B) With an olefinic dienophile:

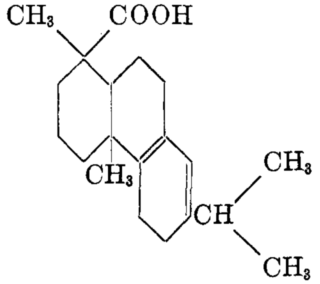


If the low-temperature adduct of cumalinic ester with maleic anhydride is esterified with methanol, carbon dioxide is eliminated. The product is not a trimellitic acid derivative but a trimesic ester. Apparently atmospheric oxidation occurs during the esterification reaction (145), for oxidation of the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

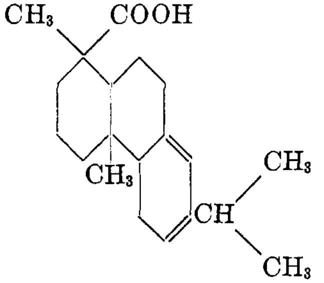
The structures of *l*-pimaric acid and of abietic acid are open to question only as far as the double-bond arrangement is concerned. Various structures have been proposed for these two acids, for their maleic anhydride adducts are identical, and one acid may be transformed into the other through the 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:



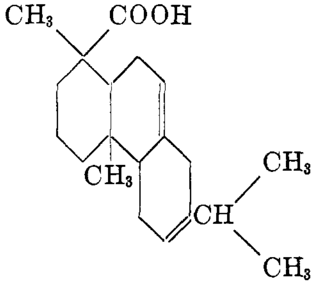
IV



V



VI



VII

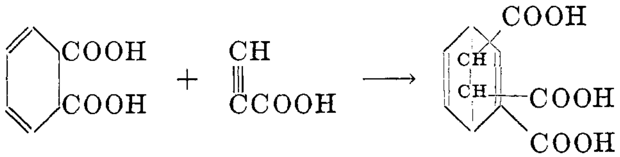
If *l*-pimaric acid has structure V, then its adduct with acetylenedicarboxylic ester should evolve ethylene on strong heating (*cf.* the section on cyclohexadiene). Sandermann (324) found that such was not the case. No olefinic gases were evolved on heating the adduct, even to charring temperatures. 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

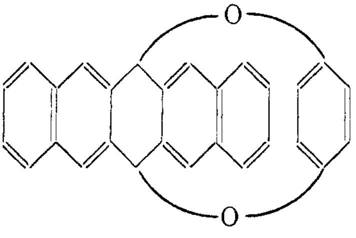
Benzene, the simplest of the aromatic hydrocarbons, does not react with maleic anhydride or with indene (291). An adduct, hypothetically obtainable from benzoic acid and maleic anhydride, probably could be obtained by addition of propiolic acid to 1,2-dihydro-*o*-phthalic acid:



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

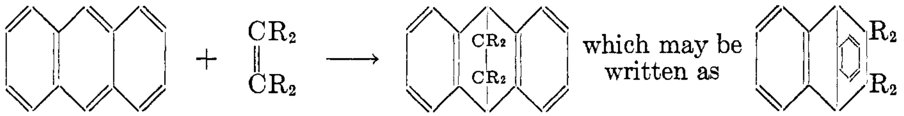
Diels and Alder, for as late as 1930 Clar and John (119) were of the opinion that the reaction product of *p*-benzoquinone and pentacene was of structure I:



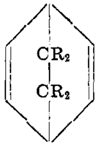
I

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

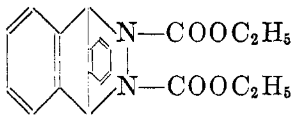
It will be recalled that the —CR_2—CR_2— bridge splits out when the adducts of cyclohexadienes with acetylenic dienophiles are heated, to yield an olefin, $CR_2{=}CR_2$. These adducts may, in a sense, be regarded as the adducts of the benzene derivative and the olefin, although such generators do not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

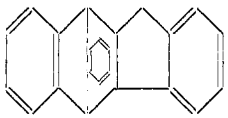
When the 9,10-substituents are alkyl groups, little effect is produced with regard to the end result of the synthesis. Usually the reaction rate is increased and the equilibrium point is nearly that of the parent hydrocarbon. Thus, 9,10-dimethylanthracene reacts much more rapidly than anthracene. 9,10-Diethylanthracene 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.

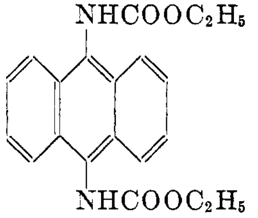
As a typical diene, anthracene adds even such dienophiles as azodicarboxylic ester (170), giving III, and indene (291) to give IV:



III



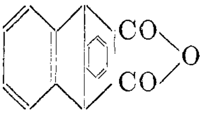
IV



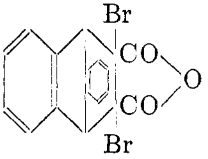
V

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).

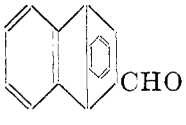
The maleic anhydride adduct of anthracene, VI, is also oxidizable to anthraquinone, as are the anthracene adducts of dibromomaleic anhydride, citraconic anhydride, and crotonic acid (149) and also the anthracene adduct of acrylic acid (73). The adduct of dibromomaleic anhydride (VII) may be debrominated 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.



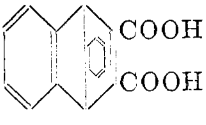
VI



VII



VIII



IX

TABLE 8

Addition of acetylenedicarboxylic ester to dienic acids and their derivatives

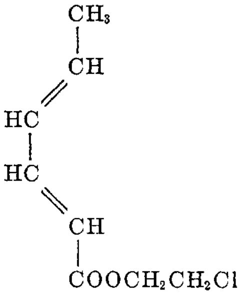
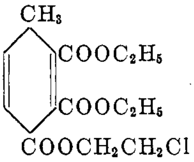
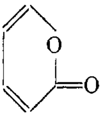
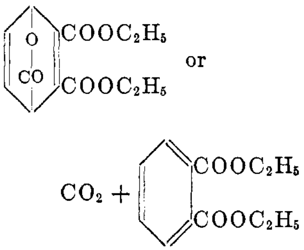
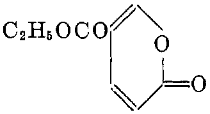
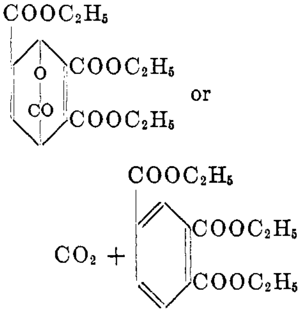
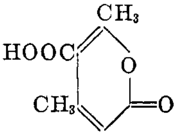
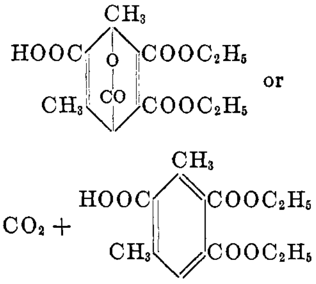
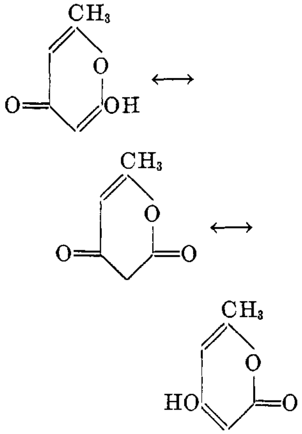
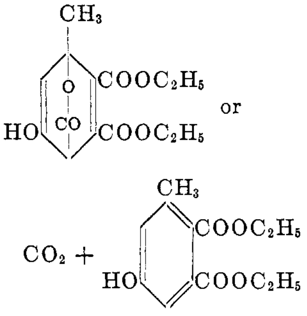
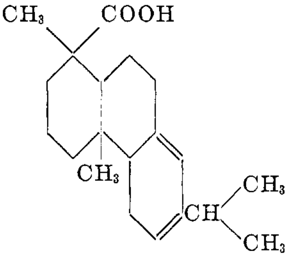
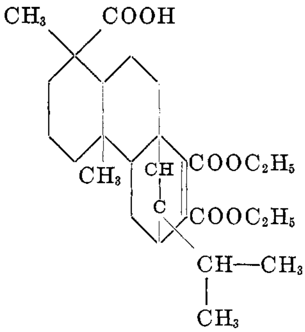
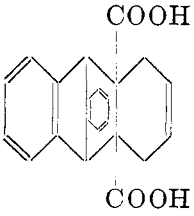
DIENE	DIENE STRUCTURE	PRODUCT STRUCTURE	REFERENCE
β-Chloroethyl sorbate			(347)
Cumalin			(14)
Cumalinic ester			(14)
Isodehydracetic acid			(14)

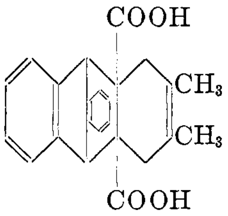
TABLE 8—*Concluded*

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

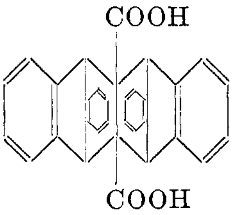
Acetylenedicarboxylic acid adds to anthracene to give an adduct (IX) which is rather reactive as a dienophile (149, 158). This adduct dienophile adds butadiene to give X, 2,3-dimethylbutadiene gives XI, and analogous compounds are formed with 1,1,3-trimethylbutadiene, cyclopentadiene, and 9-bromoanthracene. 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



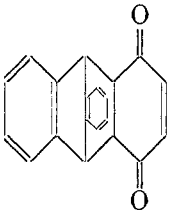
XI



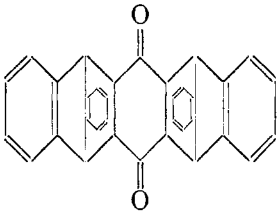
XII

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).

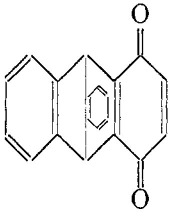
The addition of *p*-benzoquinone to anthracene yields two products. The first of them is XIII, which can add another mole of anthracene to yield the second product (XIV). Cautious oxidation of XIII yields 9,10-dihydro-9,10-endo-*o*-phenylene-1,4-anthraquinone (XV); more energetic oxidation gives 9,10-anthraquinone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



XIII

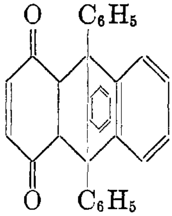


XIV

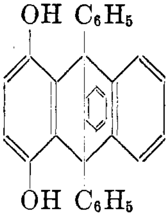


XV

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 attainment 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 (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).

TABLE 9

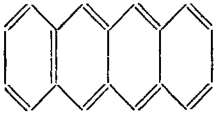
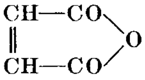
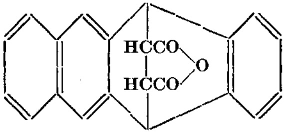
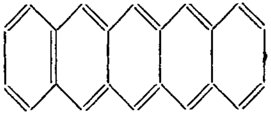
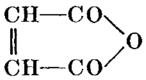
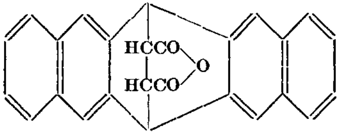
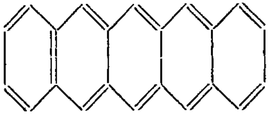
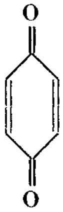
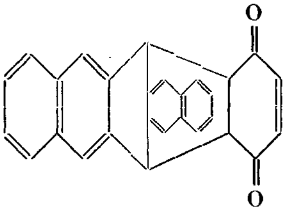
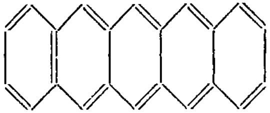
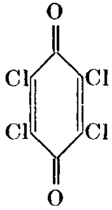
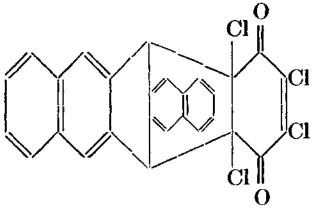
Equilibria attained in additions of maleic anhydride to anthracene derivatives in boiling xylene

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	

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)

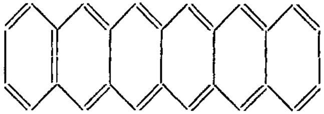
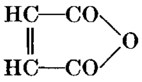
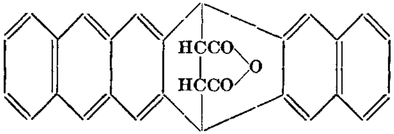
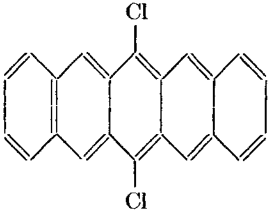
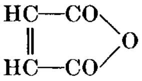
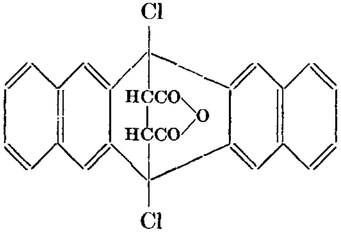
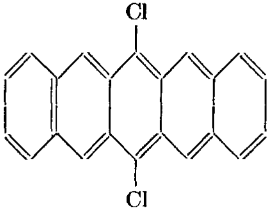
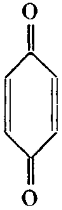
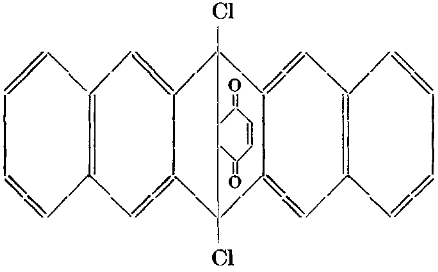
			(114)
			(109)
			(109)

TABLE 10—*Continued*

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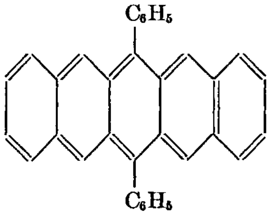
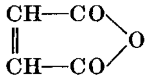
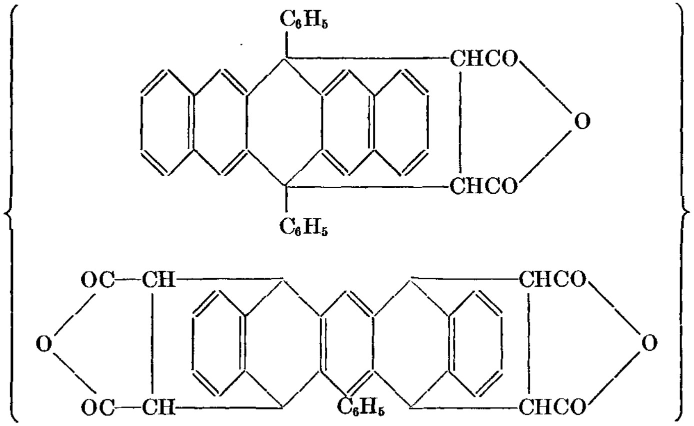
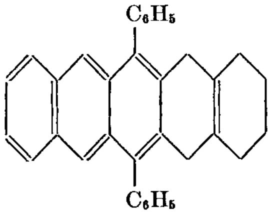
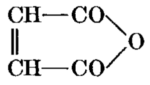
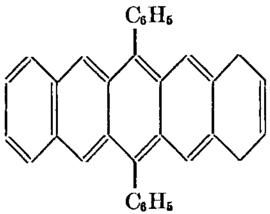
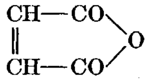
			(386)
		Adduct formed which reverts to generators on attempted isolation	(386)
		No reaction	(386)

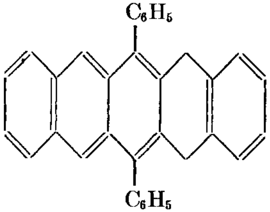
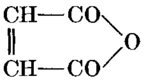
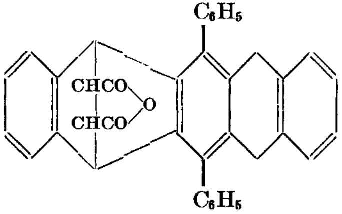
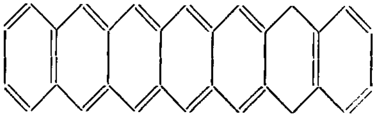
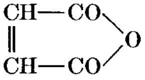
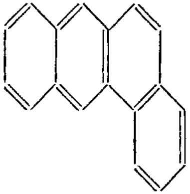
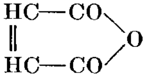
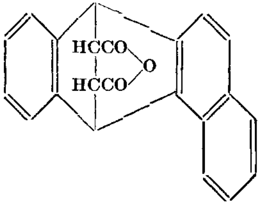
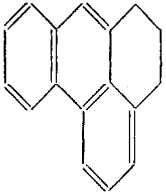
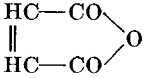
			(386)
		Reacts readily; product not isolated	(417)
			(66, 109)
		No reaction	(117)

TABLE 10—*Continued*

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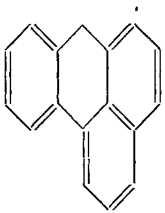
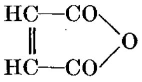
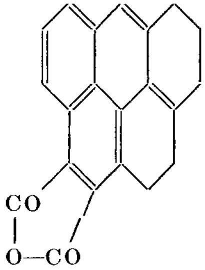
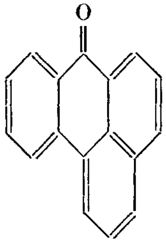
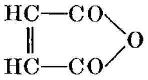
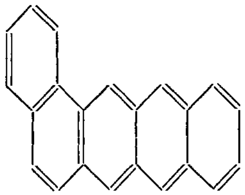
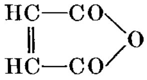
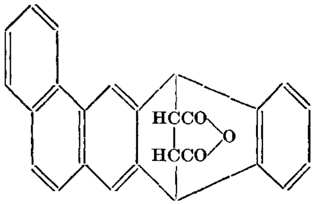
	 $\left.\begin{matrix}\mathrm{HC{-}CO} \\ \Vert \\ \mathrm{HC{-}CO}\end{matrix}\right\rangle\mathrm{O}$		(111)
	 $\left.\begin{matrix}\mathrm{HC{-}CO} \\ \Vert \\ \mathrm{HC{-}CO}\end{matrix}\right\rangle\mathrm{O}$	No reaction	(110)
	 $\left.\begin{matrix}\mathrm{HC{-}CO} \\ \Vert \\ \mathrm{HC{-}CO}\end{matrix}\right\rangle\mathrm{O}$		(120)

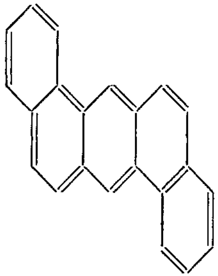
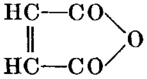
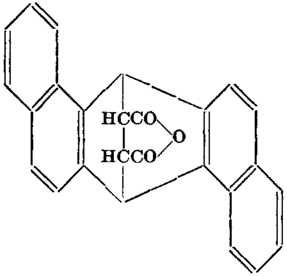
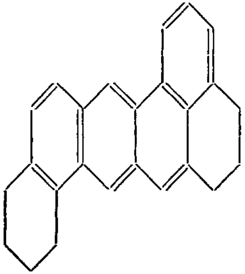
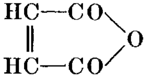
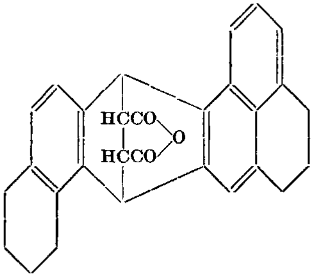
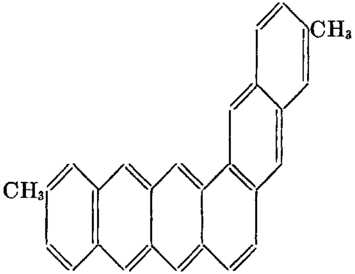
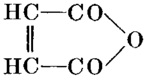
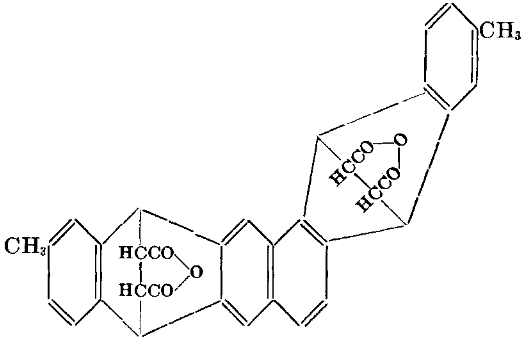
	 $\begin{array}{l}HC-CO\diagdown \\ \ \Vert \qquad\qquad O \\ HC-CO\diagup\end{array}$		(66, 124)
	 $\begin{array}{l}HC-CO\diagdown \\ \ \Vert \qquad\qquad O \\ HC-CO\diagup\end{array}$		(116)
	 $\begin{array}{l}HC-CO\diagdown \\ \ \Vert \qquad\qquad O \\ HC-CO\diagup\end{array}$		(108)

TABLE 10—*Continued*

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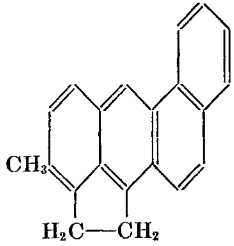
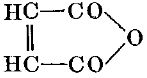
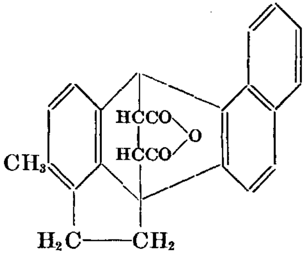
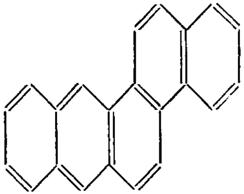
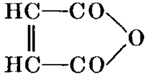
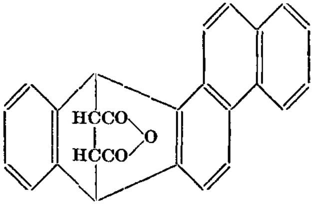
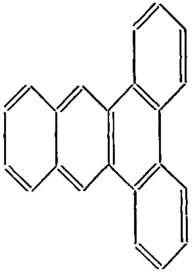
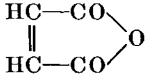
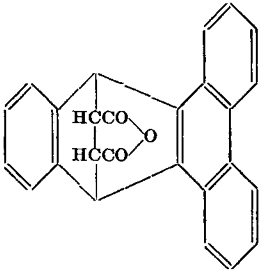
			(66)
			(120)
			(120)

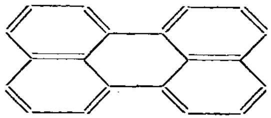
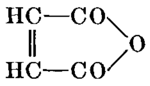
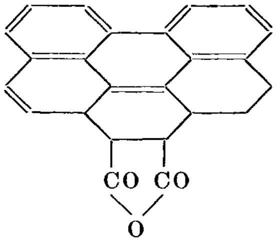
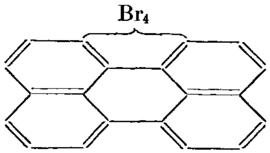
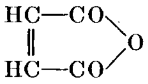
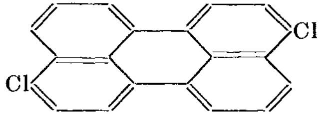
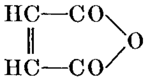
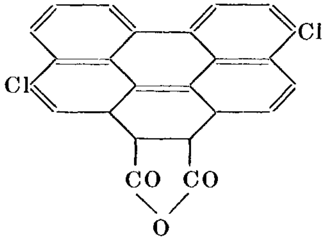
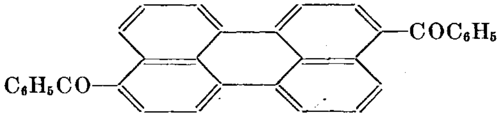
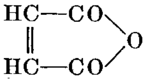
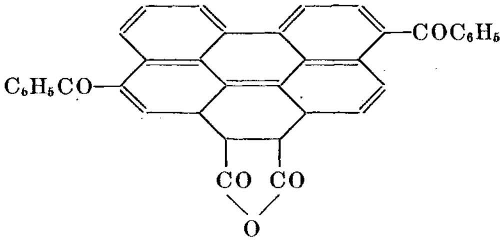
			(110, 115)
		No reaction	(377)
			(377)
			(377)

TABLE 10—*Continued*

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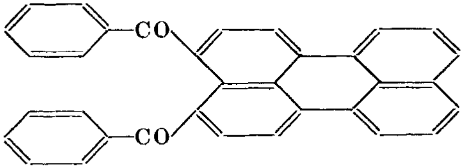
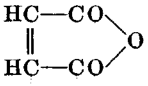
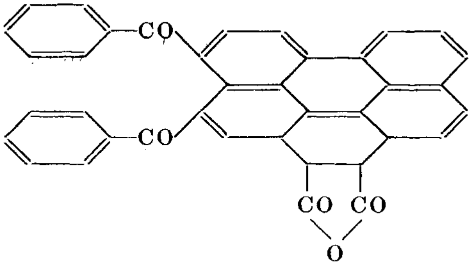
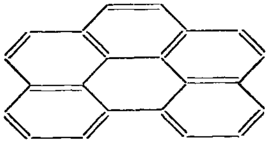
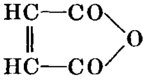
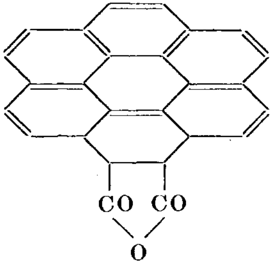
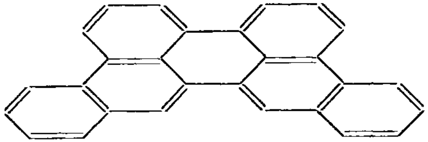
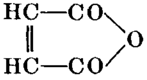
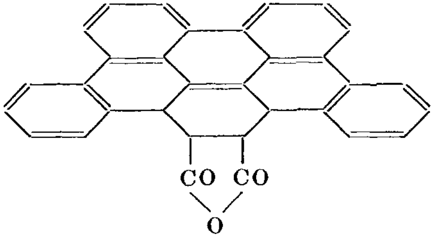
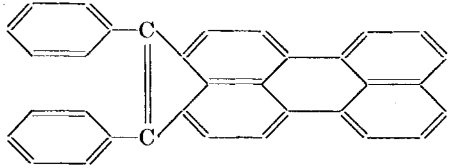
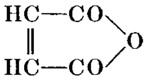
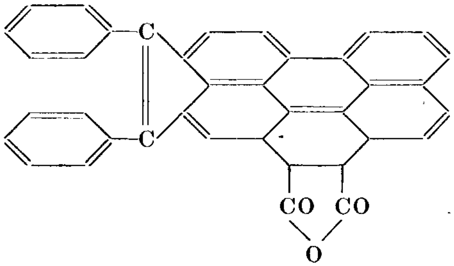
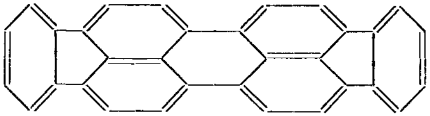
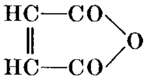
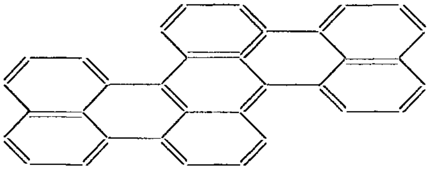
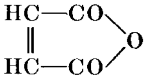
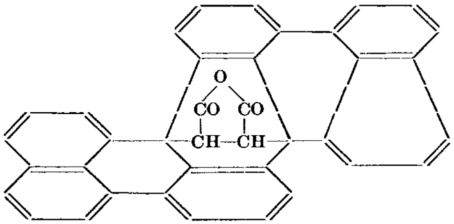
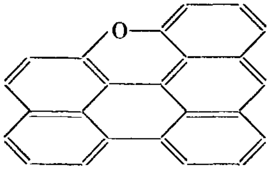
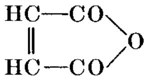
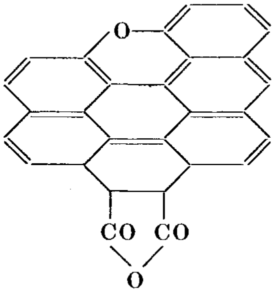
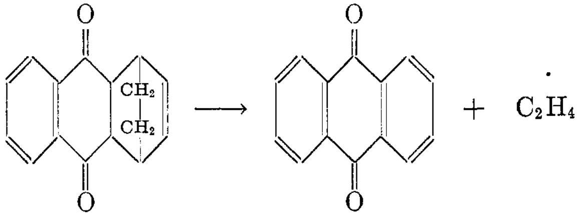
			(377)
			(110)
			(110)

	 $\begin{array}{l}\mathrm{HC-CO} \\ \Vert \qquad\quad \mathrm{O} \\ \mathrm{HC-CO}\end{array}$		(377)
	 $\begin{array}{l}\mathrm{HC-CO} \\ \Vert \qquad\quad \mathrm{O} \\ \mathrm{HC-CO}\end{array}$	No reaction	(95)
	 $\begin{array}{l}\mathrm{HC-CO} \\ \Vert \qquad\quad \mathrm{O} \\ \mathrm{HC-CO}\end{array}$		(118)
	 $\begin{array}{l}\mathrm{HC-CO} \\ \Vert \qquad\quad \mathrm{O} \\ \mathrm{HC-CO}\end{array}$		(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).

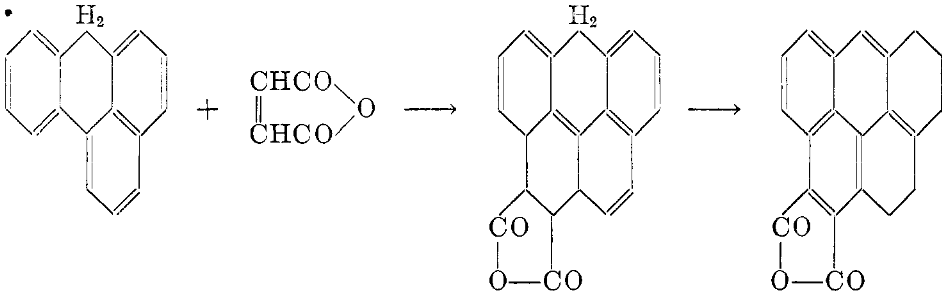
Although anthraquinone may be considered as possessing the grouping C═C—C═O, benzene rings are fused to each of these ethylenic double bonds, and this is sufficient to prohibit anthraquinone from acting as a dienophile. However, the carbonyl groups activate the benzene rings sufficiently so that anthraquinone 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

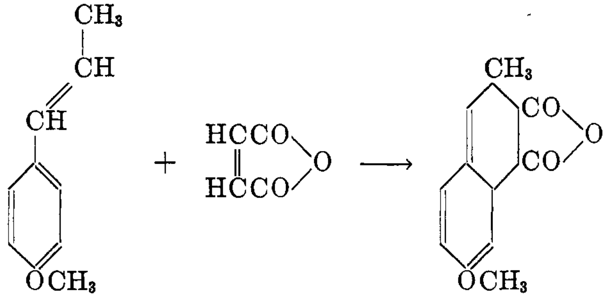
A. Vinylaromatics

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.

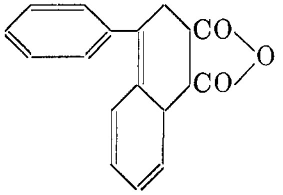
A tendency toward the addition of dienophiles according to the diene synthesis is possessed by styrene, which has been shown (*vide supra*) to possess dienophilic properties. Since butadiene, which usually acts as a diene, possesses dienophilic properties toward the cyclones (see cyclopentadienones) 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.

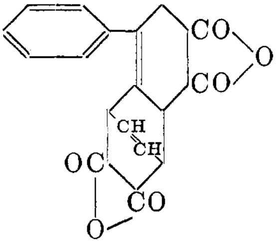
Despite the above report that no monomeric adduct is obtained from styrene and maleic anhydride, anethole (1-(*p*-methoxyphenyl)-1-propene) has been reported (289) to give an adduct with maleic anhydride which is monomeric (Hudson and Robinson (409) aver that the adduct is polymeric).



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.



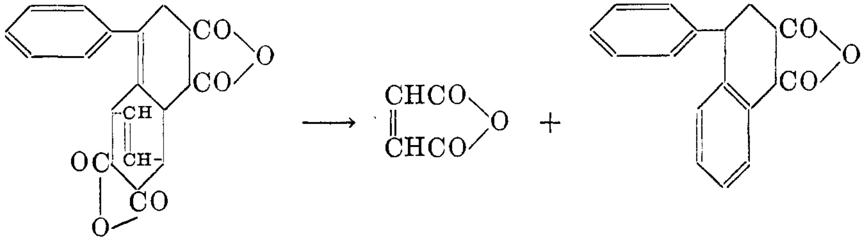
I



II

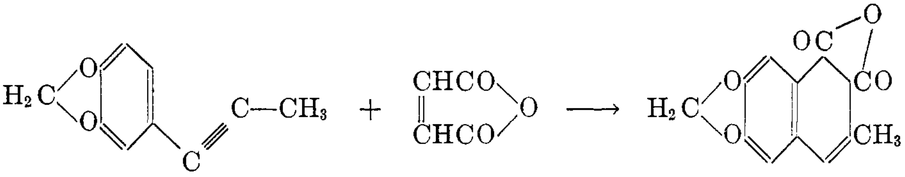
The dienophilic property of a dienophile which adds to α-phenylstyrene must be rather pronounced, for citraconic anhydride does not add (see Class A dienophiles, page 327).

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

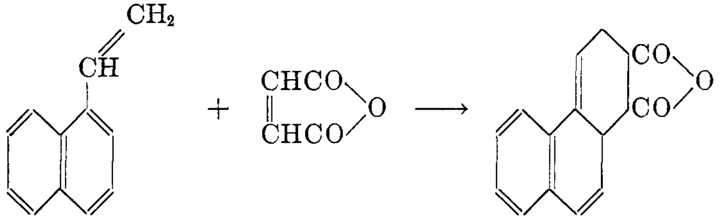


Hudson and Robinson (409) have made an extensive study of alkoxylated styrenes. Monomeric adducts are reported to form between isosafrole and maleic anhydride, diethyl maleate, and acetylenedicarboxylic ester. Isoeugenol also forms an adduct with diethyl maleate, as does its methyl ether. The ethyl ether 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:

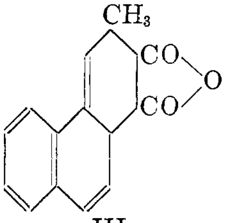


α-Vinylnaphthalene is capable of adding various dienophiles to give monomeric adducts. Since this occurs more easily than does the styrene addition, the naphthalene nucleus therefore exhibits a lower degree of aromaticity than does the benzene nucleus. One of the standards of aromatic character is the 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.

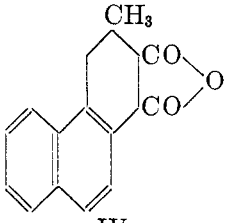


Arnold (389) reports that 5-vinyl- and 5-isopropenyl-hydrindenes polymerize in the presence of maleic anhydride. This appears to be analogous to the styrene reaction.

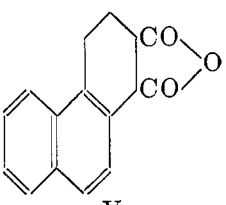
1-Propenylnaphthalene (206) does not add citraconic anhydride, but adds maleic anhydride to give III or IV. Fieser and Daudt are of the opinion that under the experimental conditions of this diene synthesis, wandering of a double bond of III occurs to give IV. This is not unlikely, but it has not been 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.



III

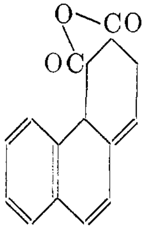


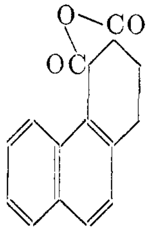
IV

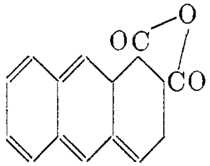


V

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.

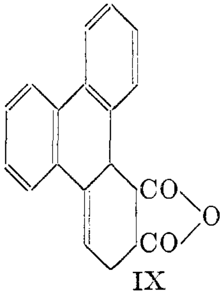

VI

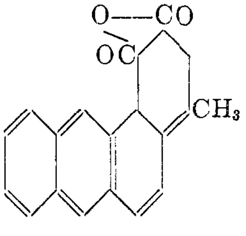

VII


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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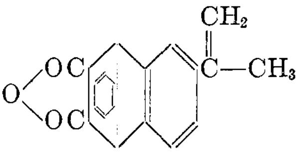
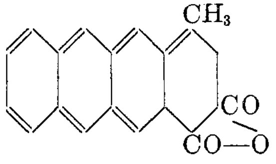
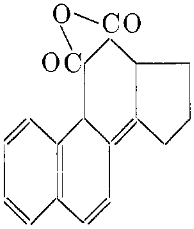

XI


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.



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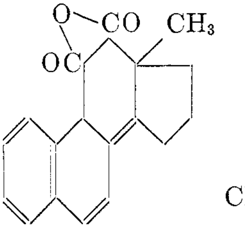
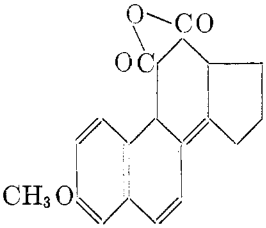


XIV



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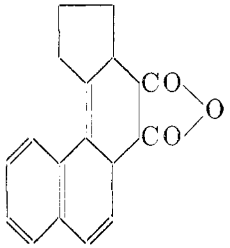
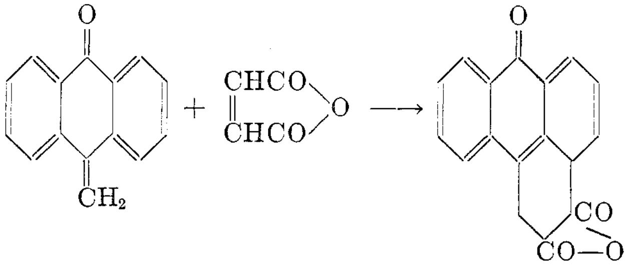


XVI

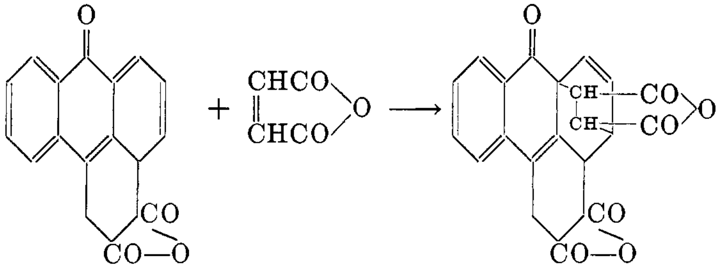
The above vinylnaphthalene derivatives which are methylated in the 2-position of the cyclenyl group add dienophiles more slowly than do their unmethylated parent compounds, for angular methyl groups appear in the adducts of the methylated vinylnaphthalene derivatives. The unmethylated cyclenylnaphthalenes 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

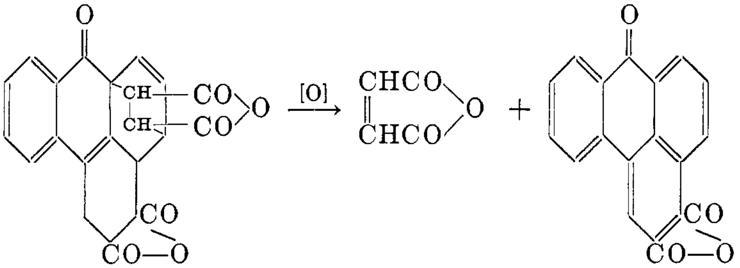
9-Methyleneanthrone and its derivatives add dienophiles readily to give partially hydrogenated derivatives of benzanthrones (113). In many cases these products are easily oxidized, often by atmospheric oxygen, to give benzanthrone derivatives (113). It is often found, therefore, that the products isolated 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



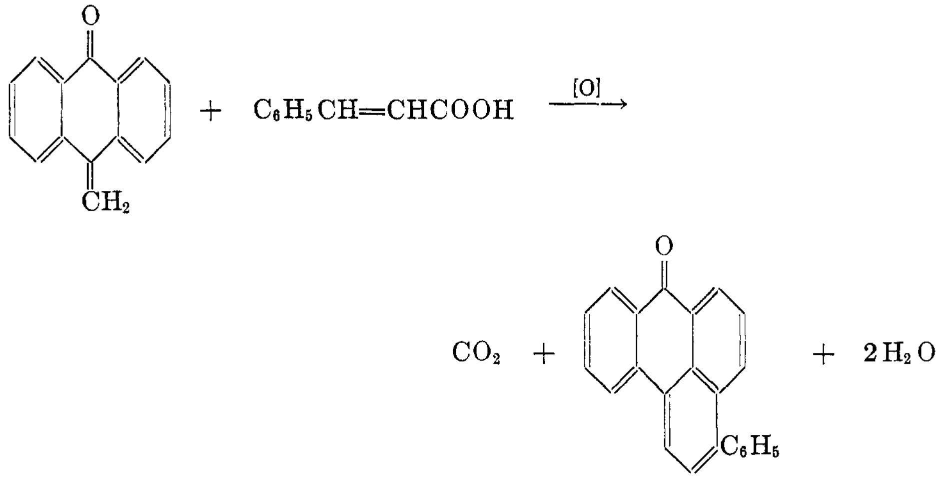
XIX

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.

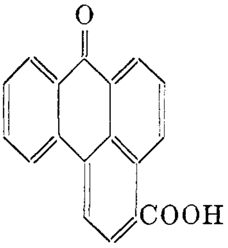
The I. G. Farbenindustrie A.-G. owns a patent (251) which covers the additions of the following dienophiles to methyleneanthrone: maleic anhydride, cinnamic acid, ethyl cinnamate, fumaric acid, crotonaldehyde, benzalacetophenone, stilbene, butadiene, and β-chloropropionic acid (which reacts by forming 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.

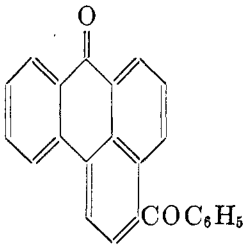
Addition of cinnamic acid (113, 251) to methyleneanthrone in boiling nitrobenzene gives *Bz*-1-phenylbenzanthrone, decarboxylation occurring during the synthesis.



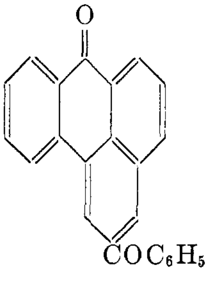
A similar decarboxylation occurs in the addition of fumaric acid, the product being XX. Benzoylethylene (47) gives what is believed to be XXI; structure XXII for the product is less likely but not impossible. Stilbene (47) gives XXIII.



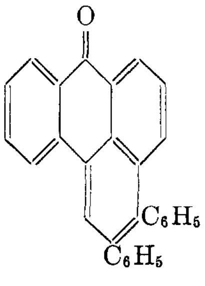
XX



XXI

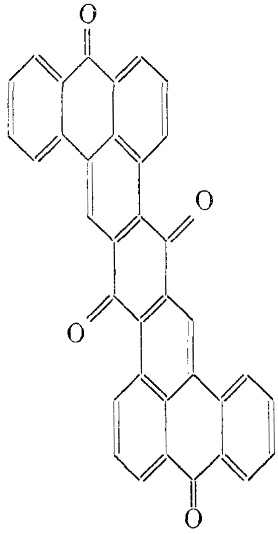


XXII

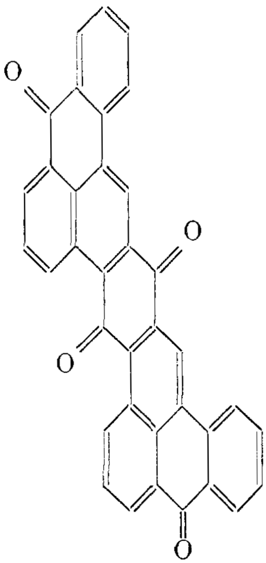


XXIII

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.

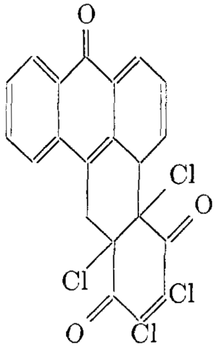


XXIV

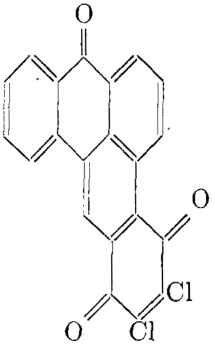


XXV

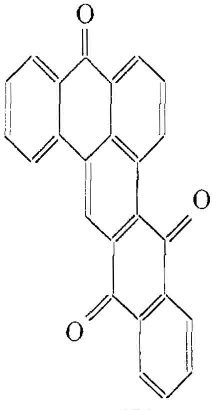
When chloranil and methyleneanthrone react, the oxidation step is unnecessary, since this was accomplished during the chlorination of the quinone. Elimination of hydrogen chloride from the initial product (XXVI) gives XXVII. Addition of excess methyleneanthrone to chloranil results in the loss of hydrogen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



XXVI



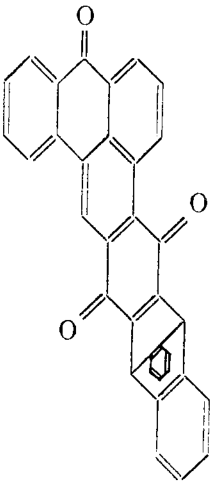
XXVII



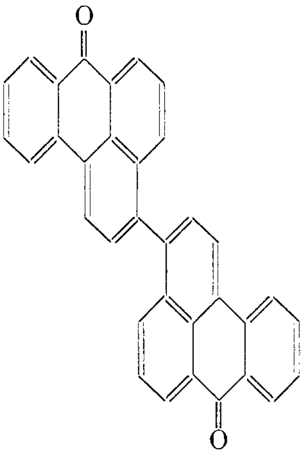
XXVIII

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.

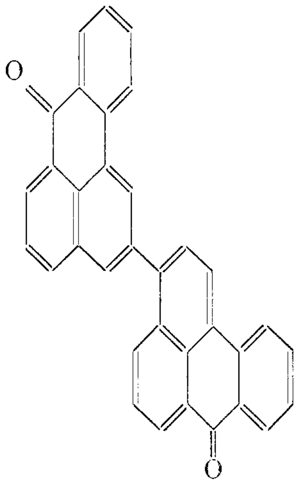
9,10-Dihydro-9,10-*o*-phenylene-1,4-anthraquinone (prepared by addition of 1 mole of anthracene to 1 mole of *p*-benzoquinone, followed by gentle oxidation of the adduct) adds to methyleneanthrone in the presence of air to give XXIX as the final product. The structure of the butadiene adduct (251) with 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



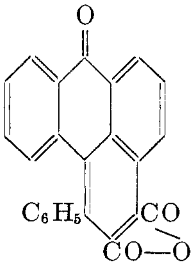
XXX



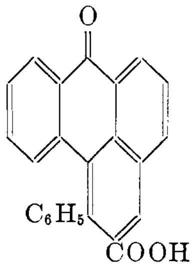
XXXI

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.

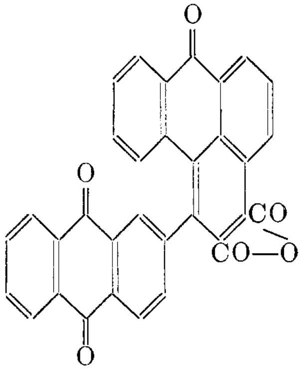
ω-(2-Anthraquinoyl)methyleneanthrone (112, 113) reacts with maleic anhydride and air to give XXXIV.



XXXII



XXXIII



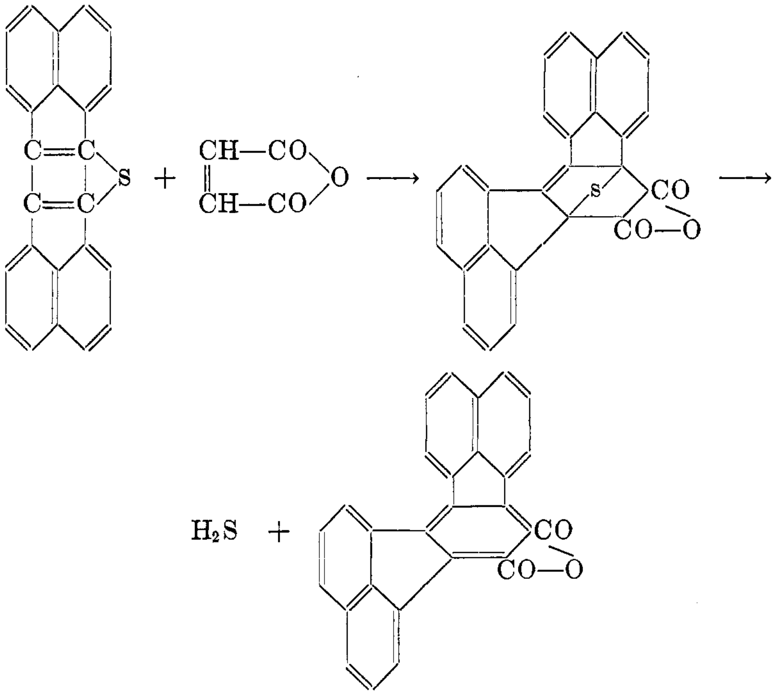
XXXIV

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:

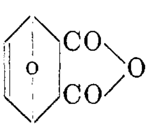


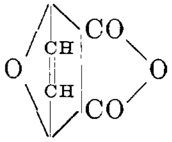
B. Furan and derivatives

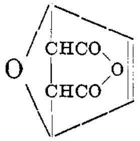
Furan contains the conjugated-double-bond system required of dienes which undergo the diene synthesis. Indeed, the most extensively studied of the dienophiles (maleic anhydride) may be regarded as the quinone of furan (301). Like the aromatic quinones, it forms colored complexes with polynuclear aromatics, 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.

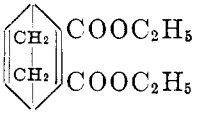
In the study of the usual two-dimensional structural pictures of these and other bridged compounds, care must be taken to avoid the impression that a so-called bridge possesses extraordinary and unique properties. A three-dimensional model of a bridged compound shows that such an assumption is invalid 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:

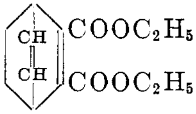

I

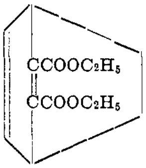

II


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

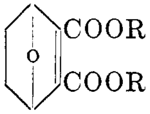

V


VI

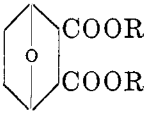
For convenience, however, the usual methods of structure designation and nomenclature of bridged compounds have been followed in this paper. Hence in discussion of adducts of furan and related compounds, reference will be made to the oxygen bridge, though it is no more of a bridge than other portions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

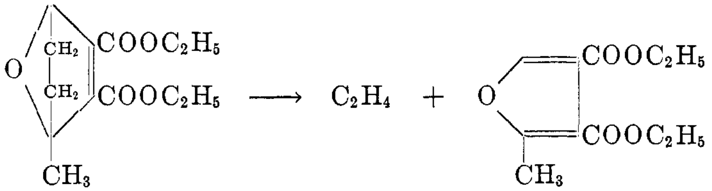


VII

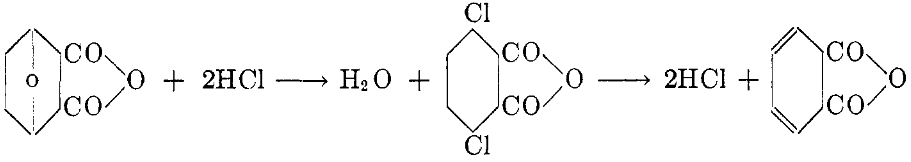


VIII

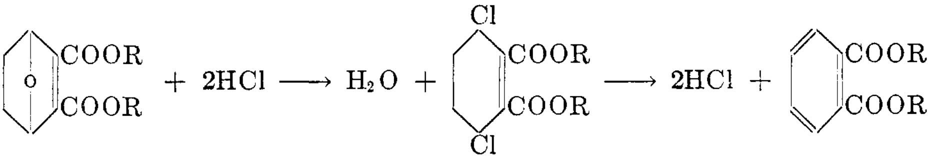
The partially hydrogenated adduct of sylvan (α-methylfuran) and acetylenedicarboxylic ester, corresponding to VII in structure, evolves ethylene on heating (14) and forms 2-methyl-3,4-furandicarboxylic ester:



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):

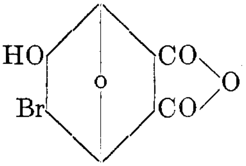


Similar treatment of the partially hydrogenated adducts of the furans with equimolar quantities of acetylenic dienophiles (14, 146) yields benzene derivatives:

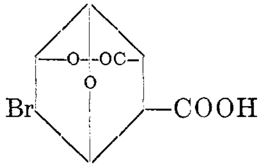


The action of hydrogen halides on the unhydrogenated adducts has not been reported, but it would most likely give a mixture of derivatives of phenol and halobenzene.

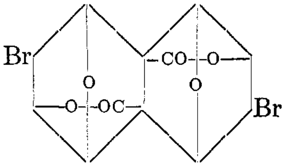
The adduct of furan and maleic anhydride will add hypobromous acid to give a compound (IX) which lactonizes easily, yielding X. This lactone acid is sensitive to hydrogen halides, for hydrogen bromide ruptures the bridge and simultaneous dehydration and dehydrohalogenation result in the formation of 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

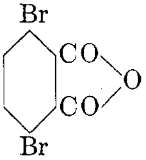


X

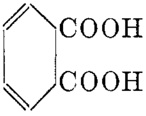


XI

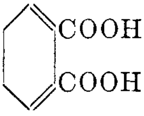
It may be seen that certain of the above reactions are adaptable to the preparation of 1,3-cyclohexadiene. The reduced adduct of furan and maleic anhydride (VIII), which is also formed by complete reduction of the adduct of equimolar quantities of furan and acetylenedicarboxylic acid, may be treated 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 cyclohexadienes. Examination of the adducts of the substituted cyclohexadienes should offer circumstantial evidence which will permit a tentative choice between formulas XIII and XIV.



XII



XIII

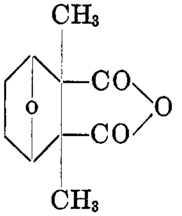


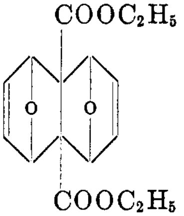
XIV

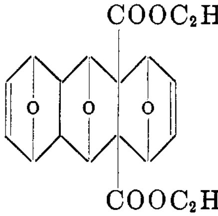
When working with the fully hydrogenated adducts of furans and maleic anhydride, one should bear in mind that these materials are vesicant (146, 148).

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.

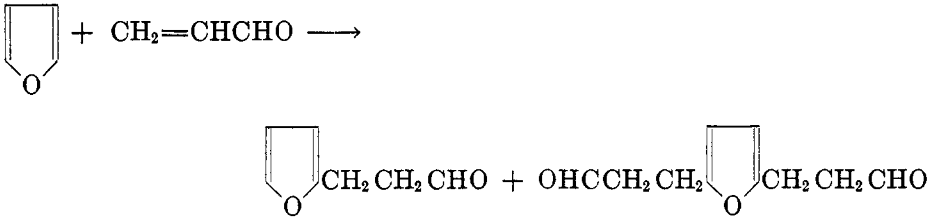
The adduct of equimolar quantities of furan and acetylenedicarboxylic ester will add a second and even a third mole of furan to give XVI and XVII, respectively (166).


XV


XVI


XVII

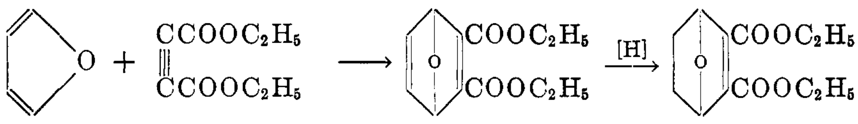
It has been found that in the presence of traces of sulfur dioxide, furan will not add acrolein according to the diene synthesis (89, 330). The reaction, which occurs only to a moderate extent, is:

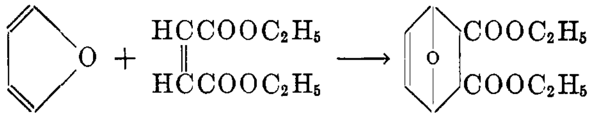


In a typical experiment, 146 g. of dry furan and 120 g. of dry acrolein were heated at 100°C. for 1 hr. with 10 mg. of sulfur dioxide dissolved in 0.5 ml. of water. Half a gram of hydroquinone had been added to stabilize the acrolein. The object of using dried materials is not known, since aqueous sulfur 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.

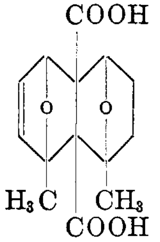
Sylvan (2-methylfuran) reacts with acetylenedicarboxylic esters and maleic anhydride and esters in the same way as does furan (9, 308). Hydrogenation of the acetylenedicarboxylic ester adducts of both furan and sylvan, using palladium and hydrogen, results in the initial reduction of one double bond 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:



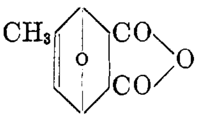


The partially hydrogenated adducts of acetylenedicarboxylic esters with furan or sylvan contain the grouping C═C—C═O; like the unhydrogenated adducts, they are able to add dienophiles. The dienophilic property is present to much the same degree as in allyl chloride (page 333), since addition of butadiene 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.

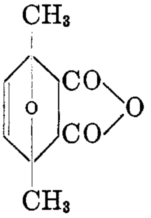
3-Methylfuran (308) has been observed to add maleic anhydride to give XIX. 2,5-Dimethylfuran adds maleic anhydride to give XX. The reduced adduct from XX is attacked by hydrobromic acid to give 3,6-dimethyl-1,2-dihydrophthalic acid. The intermediate dihalo compound could not be isolated under the conditions 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).



XVIII



XIX



XX

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.

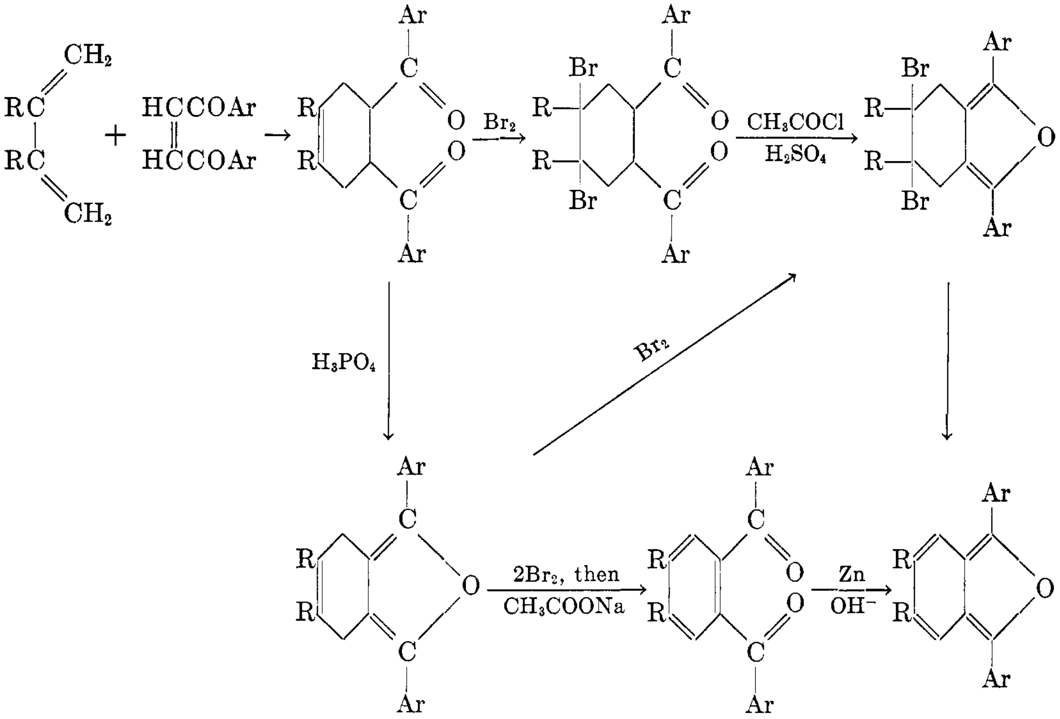
Furyl acetate is also capable of addition of dienophiles (147). The addition of maleic anhydride yields 3-acetoxymethyl-3,6-endo-oxo-1,2,3,6-tetrahydrophthalic anhydride.

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.

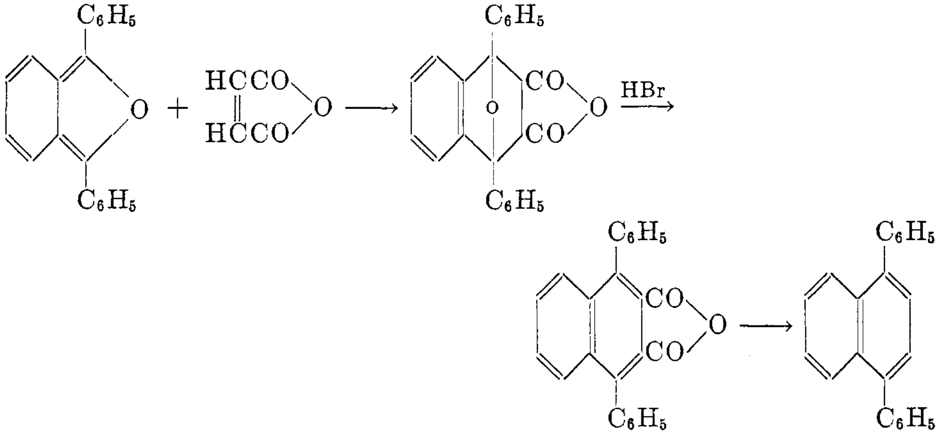
C. Isobenzofurans

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:

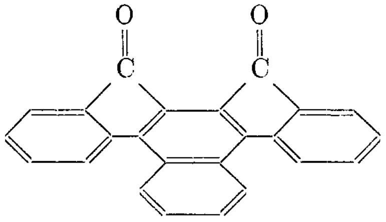


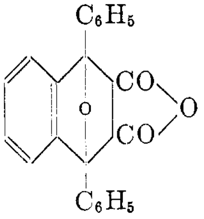
In this series of reactions, R is either hydrogen or methyl, while Ar may be phenyl, *p*-chlorophenyl, *p*-tolyl, 2-mesitylenyl, α-naphthyl, *p*-xenyl, or 3,5-dibromo-4-hydroxyphenyl (3, 4, 6, 355, 356). A portion of this series has been conducted using cyclopentadiene (3). 2,3-Dimethylbutadiene did 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).

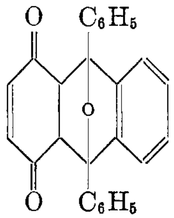

XXI


XXII

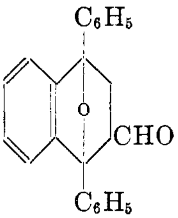
Barnett (71) added maleic anhydride to 1,3-diphenylisobenzofuran to obtain XXII. This reaction proceeds at room temperature in a dichloroethylene solution of the reactants. According to Dufraisse and Priou (188), the adduct obtained at higher temperatures differs from that obtained at room temperature, 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.

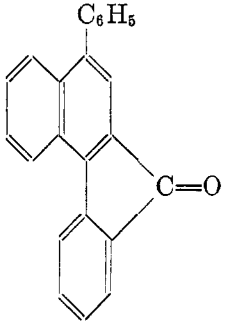
Acrolein was added to 1,3-diphenylisobenzofuran by Weiss and his coworkers (353). When the adduct (XXIV) was treated with an acetone solution of potassium permanganate, the oxide bridge was ruptured and the aldehyde group was oxidized, so that the final product was 1,4-diphenyl-2-naphthoic acid. Heating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



XXIII

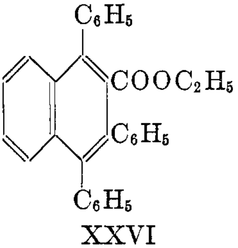


XXIV

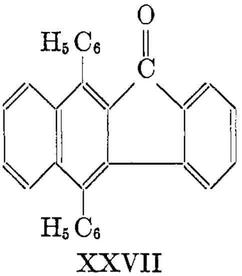


XXV

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.



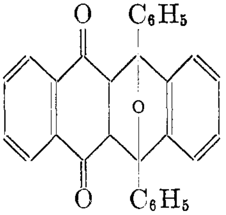
XXVI



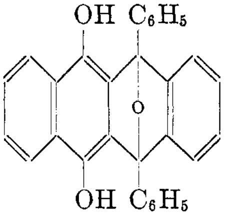
XXVII

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.

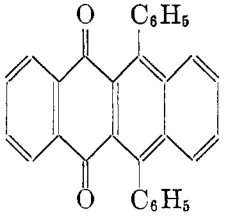
Bergmann (83) added 1,4-naphthoquinone to 1,3-diphenylisobenzofuran, and obtained 9,10-endo-oxo-9,10-diphenyl-9,9a,10,10a-tetrahydro-11,12-naphthacenequinone (XXVIII).



XXVIII



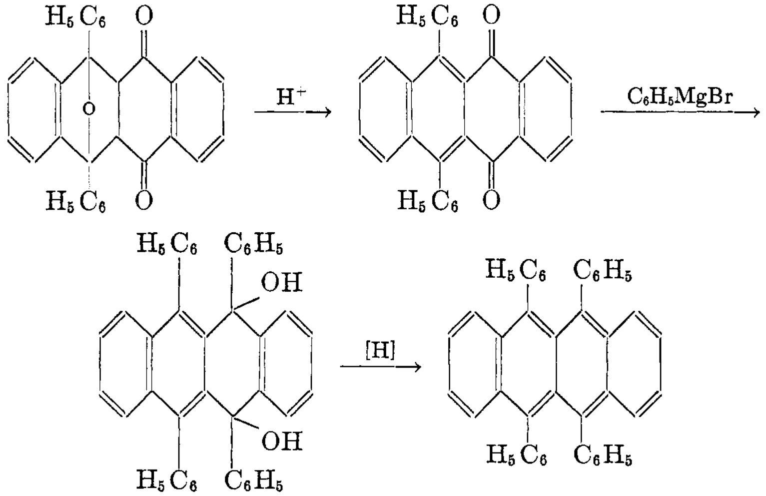
XXIX



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:



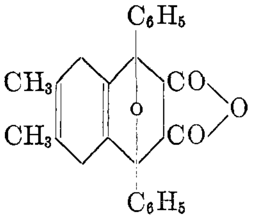
A number of other isobenzofurans have been studied, but only to a limited extent. 1,3-Bis(α-naphthyl)isobenzofuran (355) adds maleic anhydride and acrolein. The properties of these resulting adducts resemble those of the diphenyl analogs.

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.

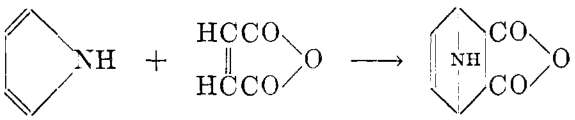


XXXI

D. *Pyrroles*

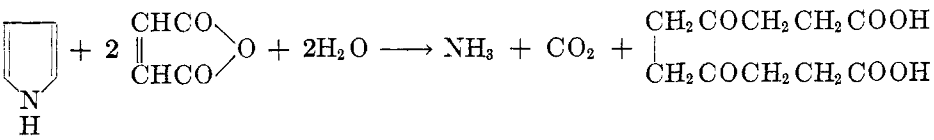
Pyrroles, the heterocyclic nitrogen atom of which occupies a position in the Periodic Table between the corresponding carbon and oxygen atoms of cyclopentadiene and furan, respectively, might be expected to act toward dienophiles as do these other two classes of matter. In no case is this true.

The reaction which would be anticipated is as follows:

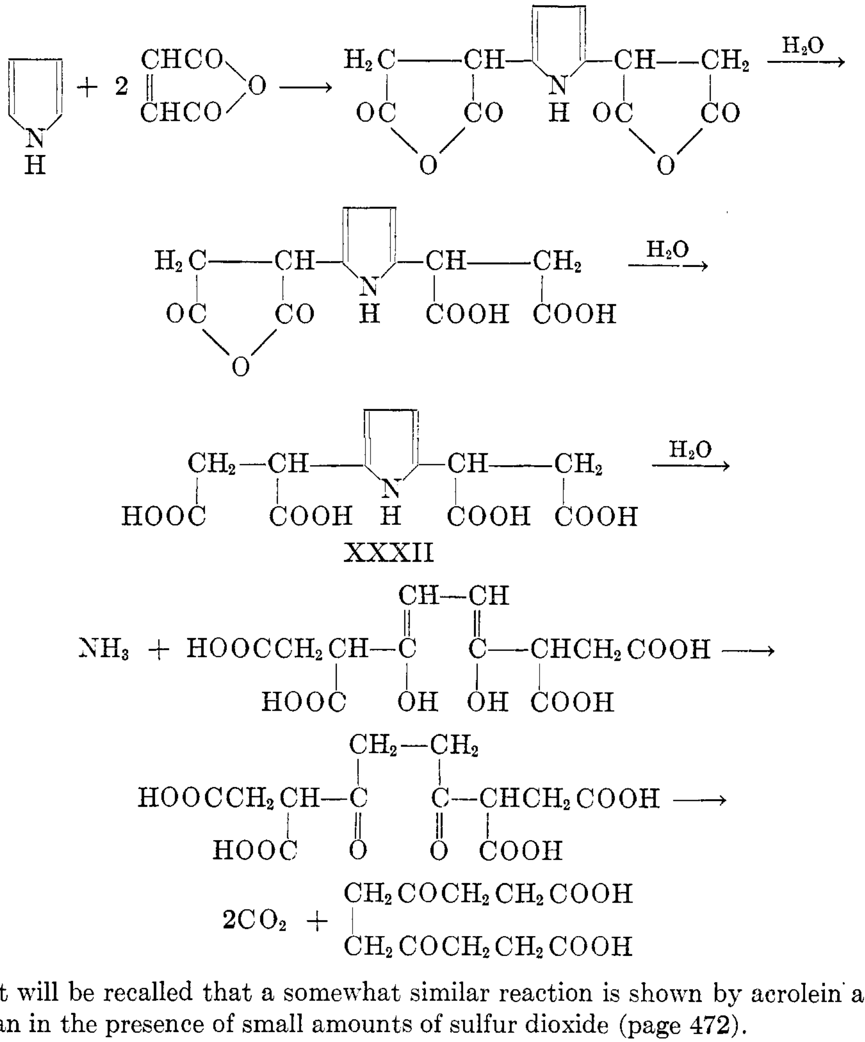


This type of reaction is not observed, and it is always found that heterocyclic dienes which contain nitrogen as a member of the ring show abnormal diene reactions. It is also found that the solvent is an important factor in determining the structure of the main product of the reaction.

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

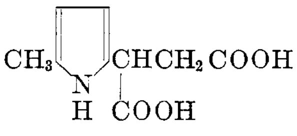


In addition, there is obtained a small amount of 2,5-pyrrolylenedisuccinic acid (XXXII), which lends credence to the following mechanism for the pyrrole reaction:



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).

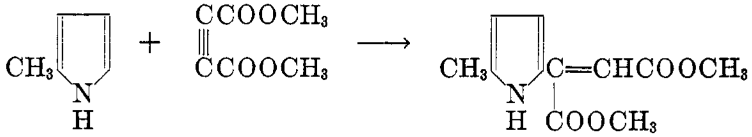
2-Methylpyrrole reacts somewhat similarly with maleic anhydride in aqueous solution to give 2-methyl-5-pyrrolylsuccinic acid (XXXIII) (156). 1-Methylpyrrole (156) reacts to give the *N*-methyl derivative of XXXII.



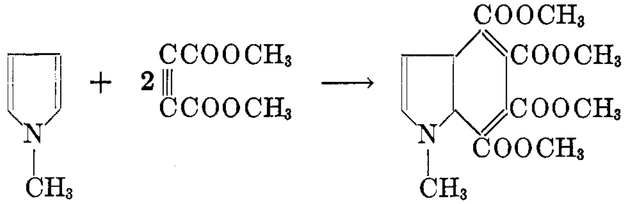
XXXIII

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

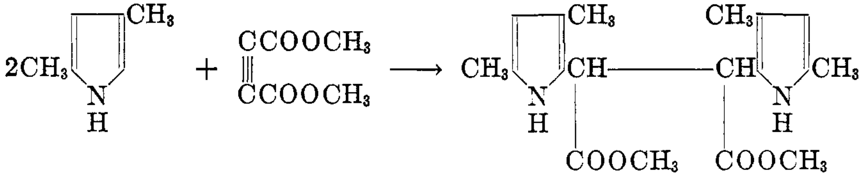
(A)



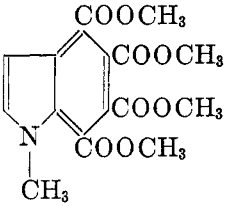
(B)



(C)



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.

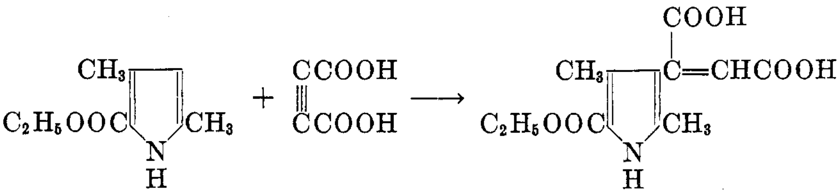


XXXIV

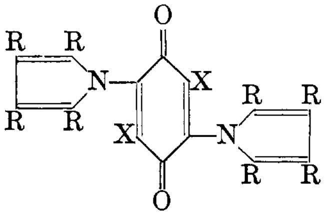
Ethyl 2,4-dimethylpyrrole-5-carboxylate reacts with acetylenedicarboxylic acid to give a product differing in type from all adducts discussed previously (225).

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.

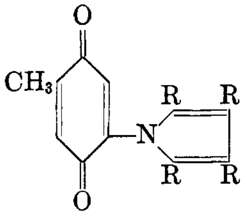
2,5-Dimethylpyrrole, 2,3,4-trimethylpyrrole, and 2,4-dimethyl-3-ethyl-pyrrole react with *p*-benzoquinone and also with 2,5-dibromo-*p*-benzoquinone (305) to give adducts of the general formula XXXV, where R is hydrogen or an alkyl group, and X is hydrogen or bromine. The by-product of the reaction is the corresponding quinhydrone or hydroquinone.



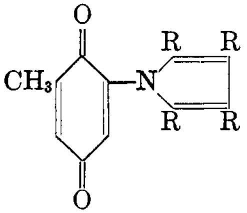
A similar reaction is shown with *p*-toluquinone (305), but only 1 mole of the pyrrole is involved. The structure of the product is not certain, being either XXXVI or XXXVII; the former is to be preferred tentatively. The inhibiting



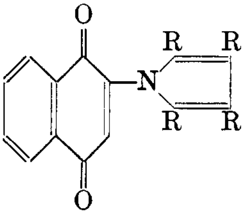
XXXV



XXXVI



XXXVII

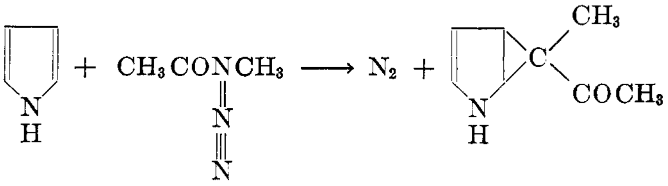


XXXVIII

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.

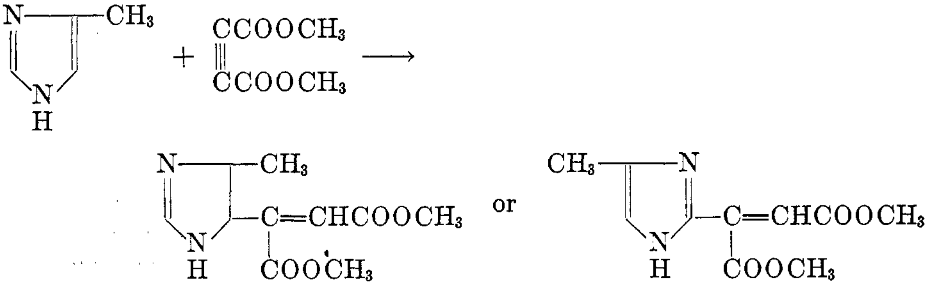
Addition of the above pyrroles also occurs to 1,4-naphthoquinone, giving XXXVIII.

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

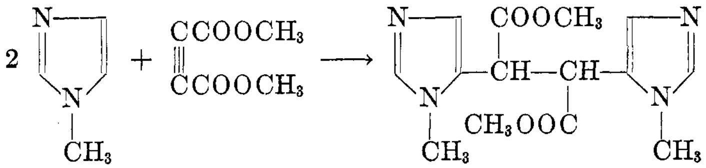


E. Imidazoles

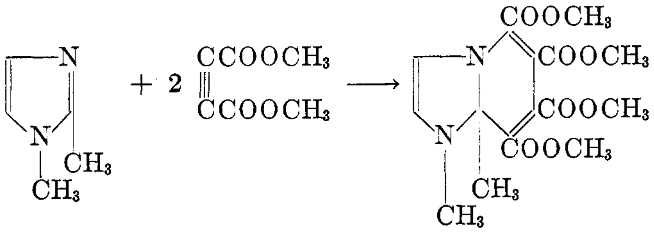
Imidazoles react with acetylenedicarboxylic esters in a manner similar to that of the pyrroles. Thus 4-methylimidazole reacts according to Type A to give one of the two possible isomers (155); it is not certain which isomer is produced.



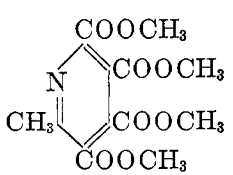
1-Methylimidazole reacts (155) according to Type C:



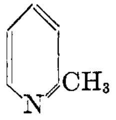
1,2-Dimethylimidazole reacts (155) according to Type B:



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



XXXIX

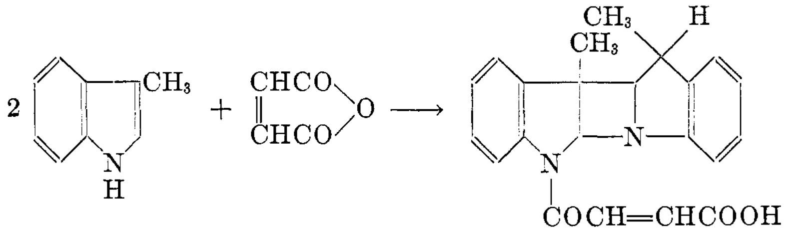


XL

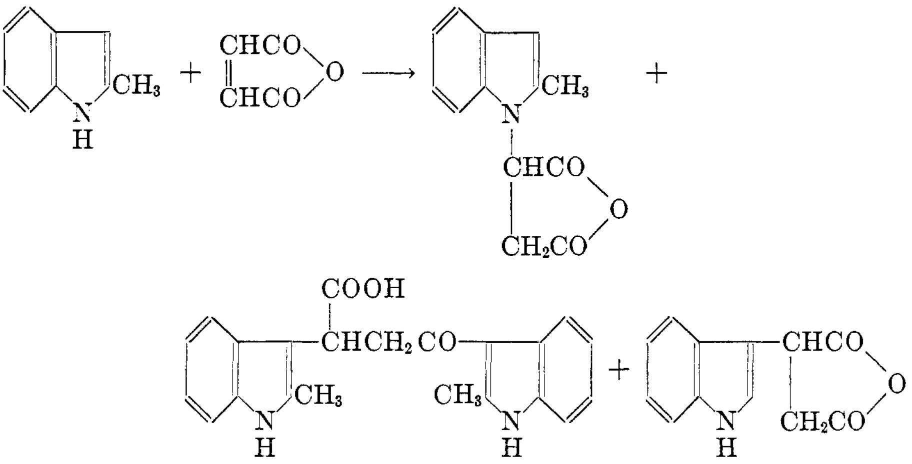
F. Indoles and carbazole

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).

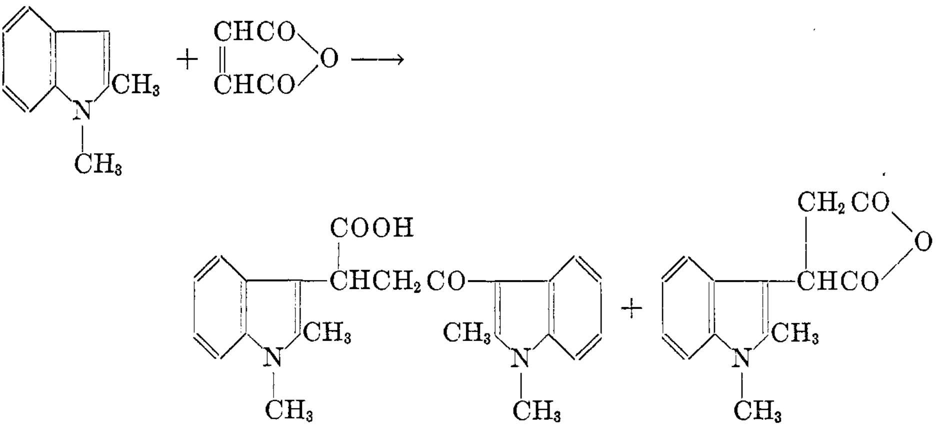
Indoles, the monobenzologs of pyrroles, react with maleic anhydride, acetylenedicarboxylic esters, and *p*-benzoquinone (143) in highly abnormal manners. For example, skatole reacts with maleic anhydride as follows:



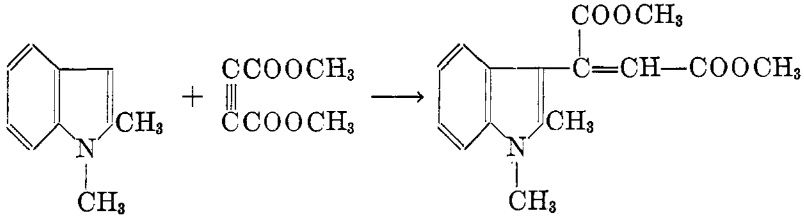
Indole reacts in a manner identical with skatole, but α-methylindole reacts in a most original manner to give three products:



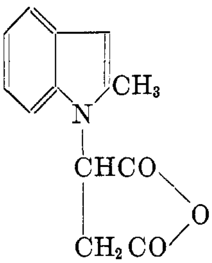
1,2-Dimethylindole reacts in a manner similar to α-methylindole, but does not form the *N*-substituted type of compound.

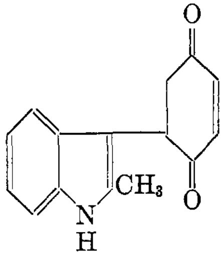


It reacts somewhat similarly with the dimethyl ester of acetylenedicarboxylic acid.



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

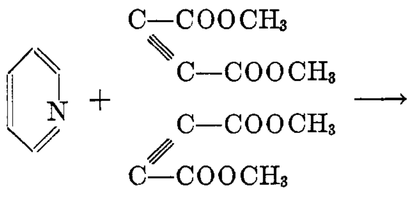

XLII

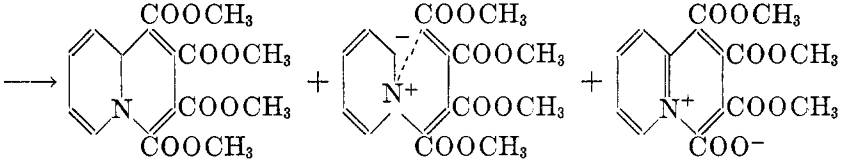
Unlike the pyrroles, azibutanone is without action on indole, skatole, and 2-methylindole (163).

G. Pyridine, its derivatives, and its benzologs

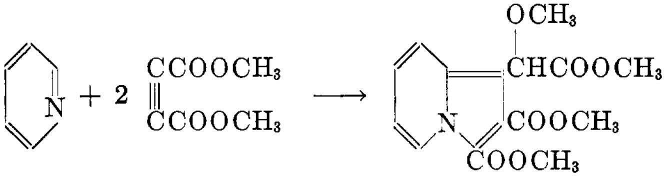
The reactions of pyridine as a diene may be regarded, on initial consideration, as being those of the alternating double bonds of the Kekulé structure. However, the reaction products of this as well as of the other nitrogenous heterocycles are not those anticipated from a consideration of the simple 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):



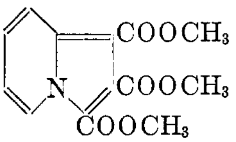


In methanol solution at 0°C., the product differs from that obtained in ether (164).

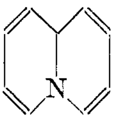


At higher temperatures, or by treatment of the above product with bromine in methanol solution, there is also obtained trimethyl indolizintricarboxylate (XLIII).

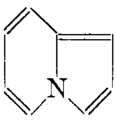
In the interests of nomenclature, it must be stated that the parent compounds XLIV and XLV are named quinizolin and indolizin, respectively. In the literature of Diels and Alder, tetramethyl quinizolin-1,2,3,4-tetracarboxylate (XLVI) is referred to as "the yellow substance", the carbide-type of intermediate (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 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).



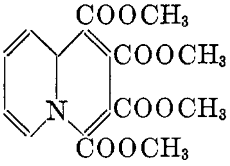
XLIII



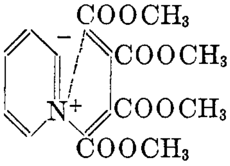
XLIV



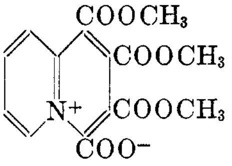
XLV



XLVI

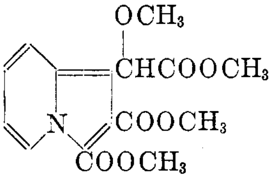


XLVII

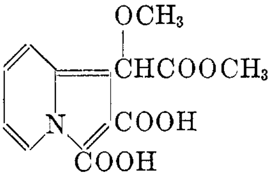


XLVIII

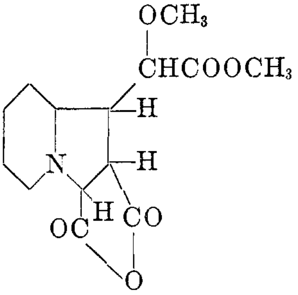
Adduct XLIX, from pyridine and acetylenedicarboxylic dimethyl ester in methanol solution at 0°C., may be reduced catalytically to a tetrahydro compound. It is attacked by acetic anhydride, suffering replacement of a



XLIX

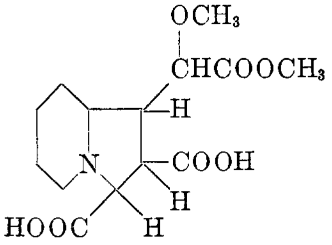


L

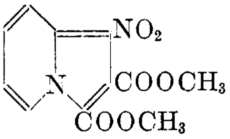


LI

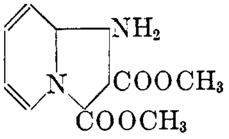
—$COOCH_3$ group by an acetyl group (164). XLIX is saponifiable to a dicarboxylic acid (L), hydrogenation of which followed by dehydration with acetic acid yields an anhydride (LI). If hydrogenation precedes saponification, the final product is the acid (LII), which does not form an anhydride because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



LII

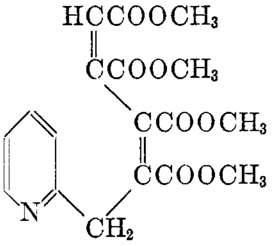


LIII

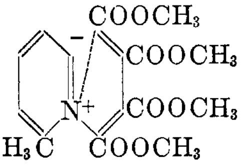


LIV

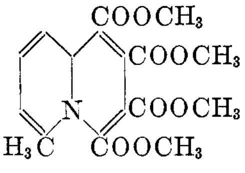
The —$CH(OCH_3)COOCH_3$ side chain of XLIX is readily removed by action of an acetic acid solution of nitric acid to give LIII, which can be easily reduced to give LIV.



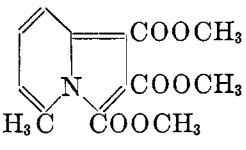
LV



LVI



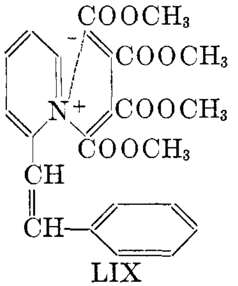
LVII



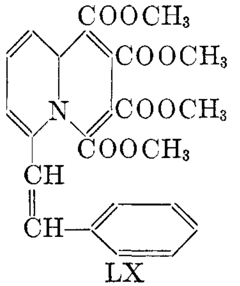
LVIII

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).

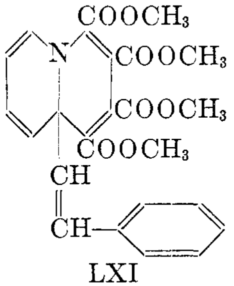
The reaction of 2-stilbazole (165) with acetylenedicarboxylic dimethyl ester in ether solution proceeds to give an orange labile compound (LIX), which is converted by heat into the first stable addition product (LX). Further heating produces the second stable addition product (LXI), which is unique in 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 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.



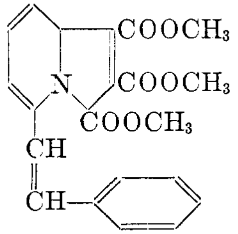
LIX



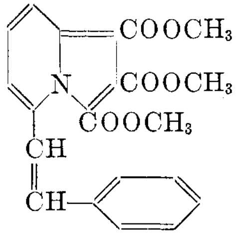
LX



LXI

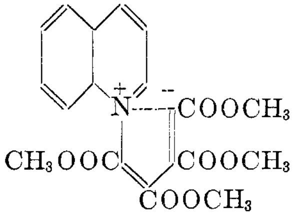


LXII

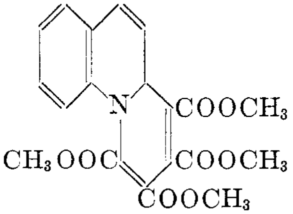


LXIII

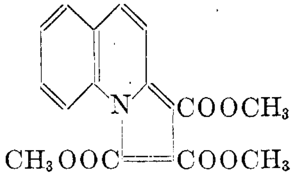
Quinoline (141, 155) reacts with acetylenedicarboxylic dimethyl ester in ether solution much as does pyridine, for it forms a yellow labile product (LXIV), which is transformed by heat into red tetramethyl 5,6-benzquinizolin-1,2,3,4-tetracarboxylate (LXV). Like the corresponding quinzolin derivative,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



LXIV

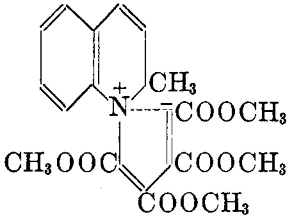


LXV

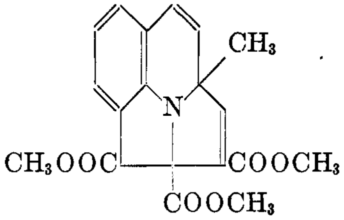


LXVI

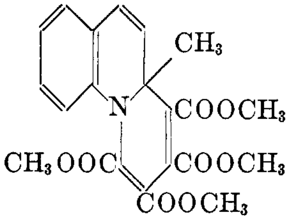
α-Quinaldine (155) reacts with an ether solution of dimethyl acetylenedicarboxylate to give a labile compound of anticipated formula (LXVII). It is heat-stabilized to give a compound first thought to be LXIX, but this was shown to be erroneous, for the compound was LXVIII. During the heat stabilization LXX is also formed through condensation with the reactive methyl group, followed by rearrangement.



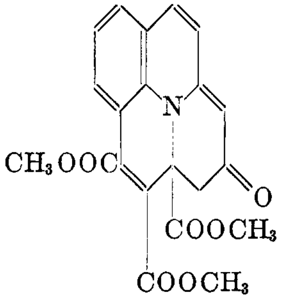
LXVII



LXVIII



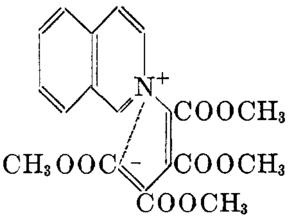
LXIX



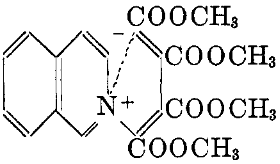
LXX

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

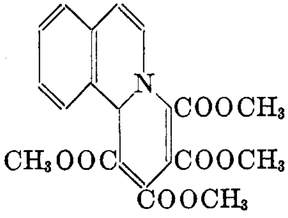
Isoquinoline (155, 159) reacts with acetylenedicarboxylic dimethyl ester in ether solution to give, mainly, an orange-yellow labile adduct to which structure LXXI has been assigned. A small amount of a red isomer is also produced, to which structure LXXII has been assigned. LXXII is heat-stabilized to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



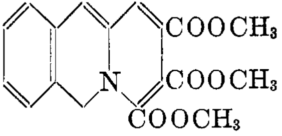
LXXI



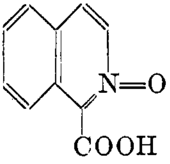
LXXII



LXXIII



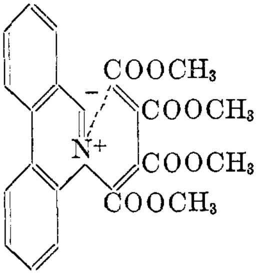
LXXIV



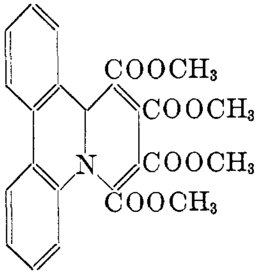
LXXV

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

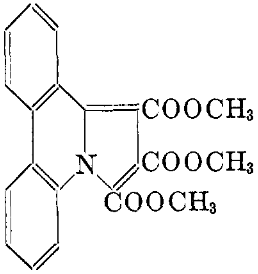
9-Phenanthridine (174) acts much in the same manner as pyridine and quinoline when treated with acetylenedicarboxylic dimethyl ester. The first product is a labile adduct (LXXVI); the stable adduct (LXXVII) is obtained by boiling LXXVI first with quinoline and then with ethyl alcohol. Crystallization of LXXVI from ether or acetonitrile gives the indolizin compound (LXXVIII). Crystallization from methanol gives LXXIX.



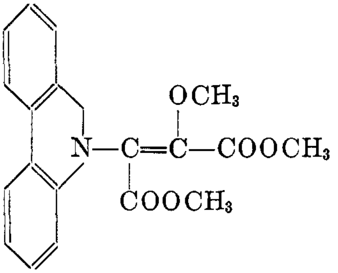
LXXVI



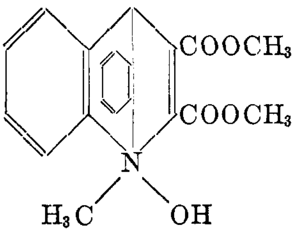
LXXVII



LXXVIII



LXXIX

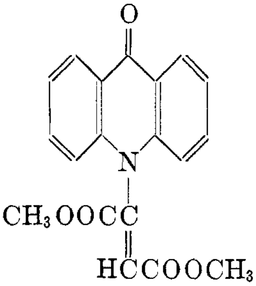


LXXX

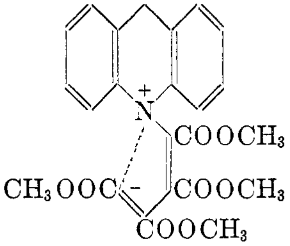
Acridine was treated with maleic anhydride by Barnett (72), who failed to obtain an adduct. Diels and his students (173) obtained various products with acridine and acetylenedicarboxylic dimethyl ester. Refluxing the two reactants in methanol for two days gives the bridged quaternary hydroxide (LXXX); 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

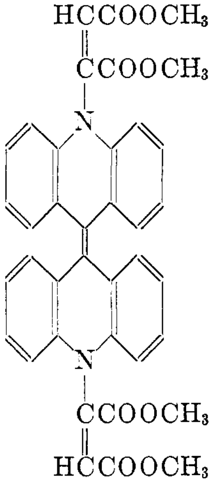
(LXXXII) with perhydrol gives a 90 per cent yield of the *cis*-form of LXXXI plus small amounts of LXXXIII.



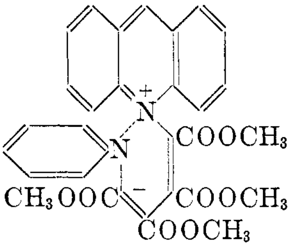
LXXXI



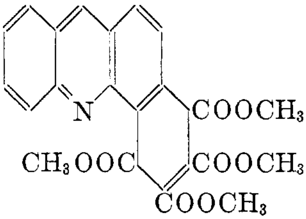
LXXXII



LXXXIII



LXXXIV



LXXXV

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

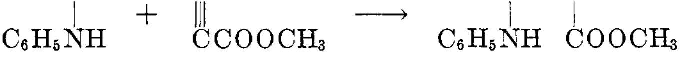
An abnormal stable adduct, LXXXV, is formed by dissolving LXXXII in concentrated sulfuric acid, followed by dilution with water.

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.

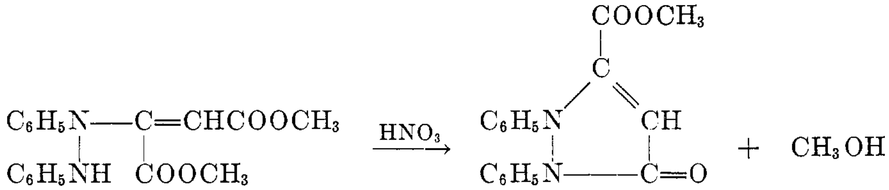
A. Hydrazines

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



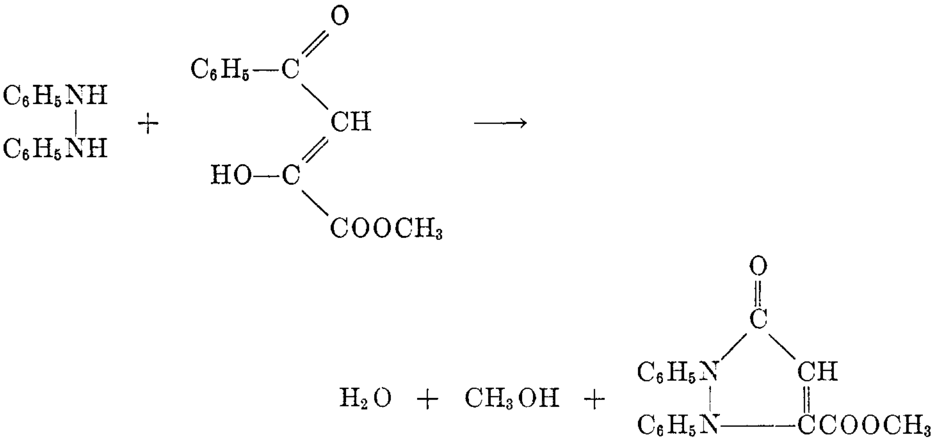
$$\begin{array}{l} \mathrm{C_6H_5NH} \\ \ \ \ \ \ \ \ | \\ \mathrm{C_6H_5NH} \end{array} + \begin{array}{l} \mathrm{CCOOCH_3} \\ \ ||| \\ \mathrm{CCOOCH_3} \end{array} \longrightarrow \begin{array}{ll} \mathrm{C_6H_5N} \text{—} & \mathrm{C{=}CHCOOCH_3} \\ \ \ \ \ \ \ \ | & | \\ \mathrm{C_6H_5NH} & \mathrm{COOCH_3} \end{array}$$

Nitric acid acts upon the adduct:

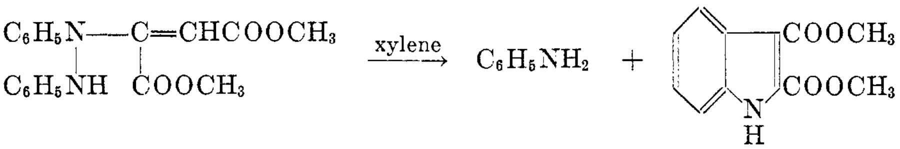


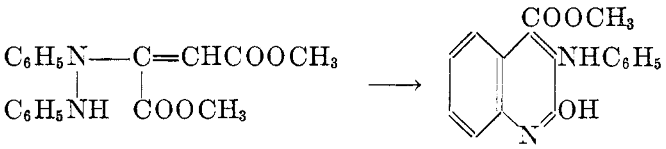
If the formation of the adduct is conducted in acetic acid solution instead of methanol, the second compound (produced above by means of nitric acid) is formed directly.

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



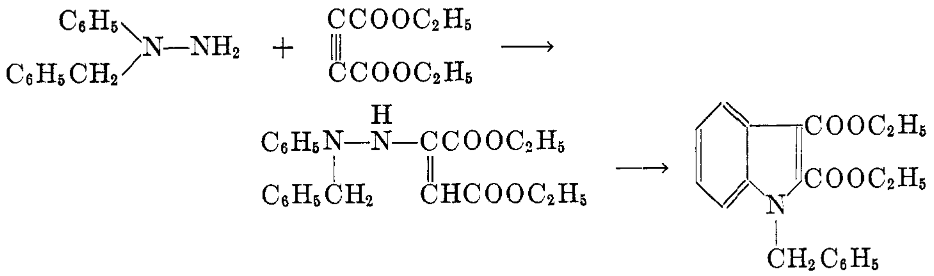
The adducts undergo a number of reactions, two of the most important being the conversions to indole and quinoline derivatives. Heating in xylene yields indole derivatives, while heat alone or heating in pyridine or dimethylaniline yields quinoline derivatives:



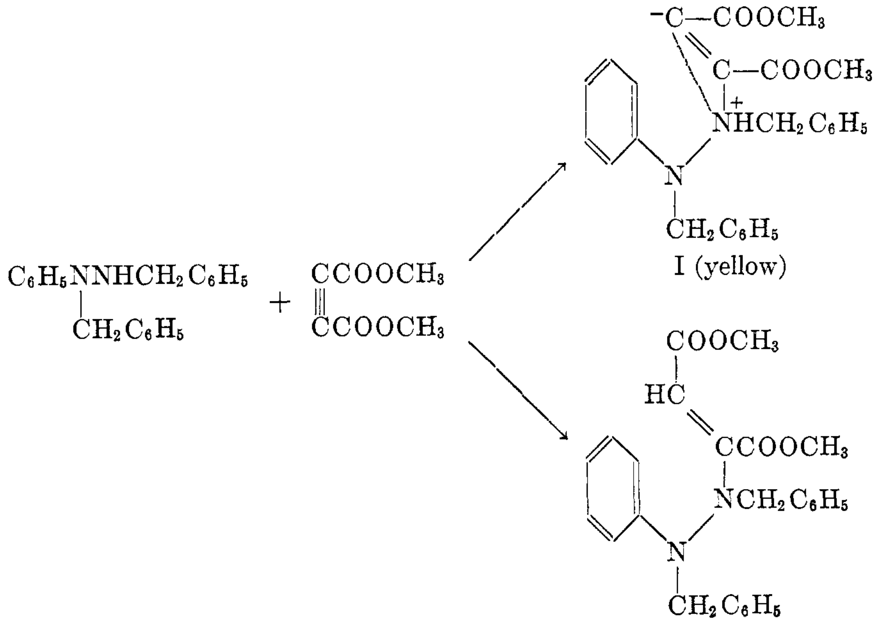


In methanol solution, *p,p*′-hydrazotoluene and *N*-phenyl-*N*′-benzylhydrazine (169) give compounds corresponding to that from hydrazobenzene and acetylenedicarboxylic dimethyl ester in methanol solution. Analogous compounds are also formed by *sym*-dibenzylhydrazine and tribenzylhydrazine.

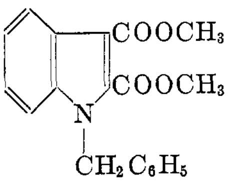
Unsymmetrical benzylphenylhydrazine also gives an analogous adduct in cold methanol; the adduct is, however, more labile than the adducts from hydrazines with one or two substituents on each nitrogen atom. In hot water, the adduct forms the indole type with loss of ammonia:

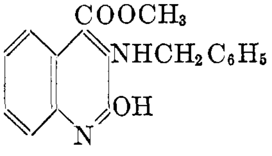


1-Phenyl-1,2-dibenzylhydrazine resembles both pyridine and the above hydrazines in its reaction with acetylenedicarboxylic dimethyl ester, giving a mixture of I and II.


I (yellow)

II (white)

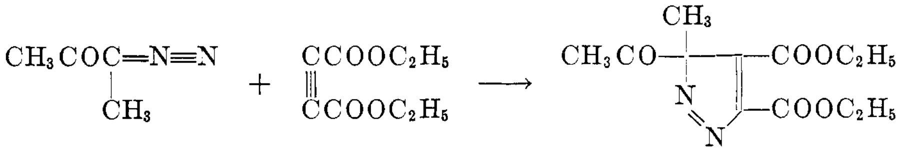

III

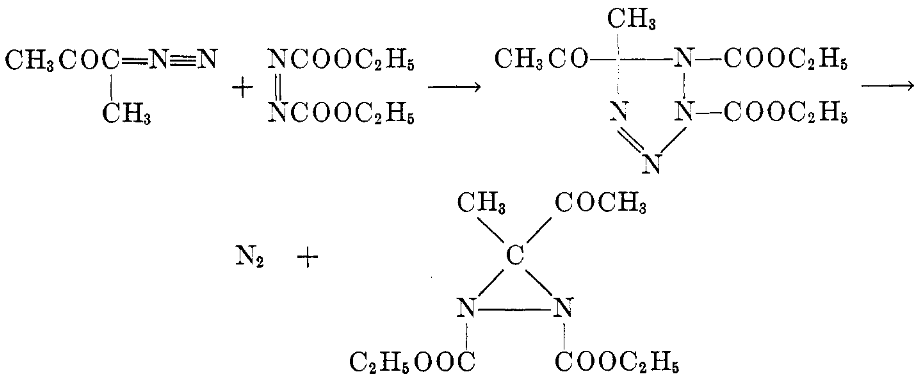

IV

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.

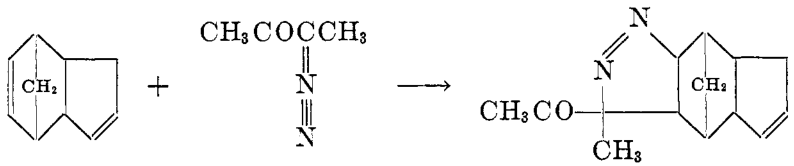
B. Azibutanone

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 aliphatic dienes or monomeric cyclopentadiene. It reacts violently with acetylenedicarboxylic ester and with azodicarboxylic ester:

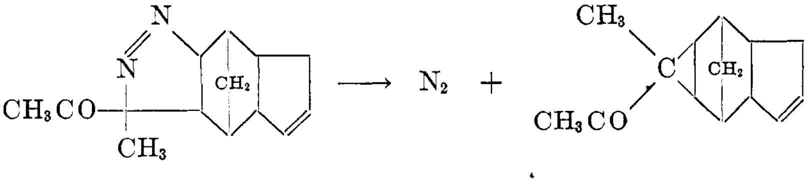




Azibutanone also reacts with the highly active double bond of the bicycloheptene derivatives; for example, the reaction with cyclopentadiene dimer is as follows:



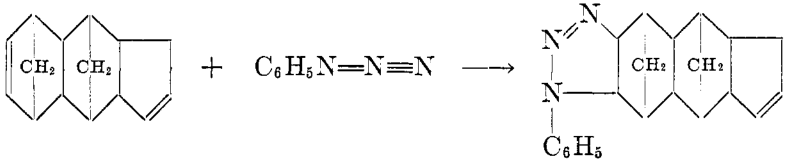
The adduct loses nitrogen on vacuum distillation:



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:

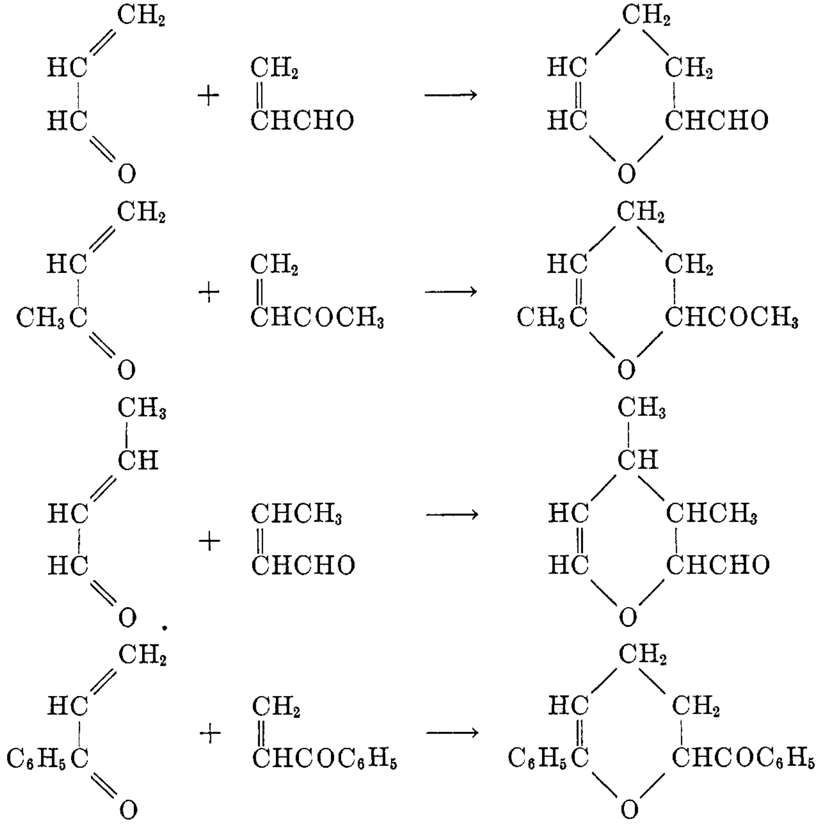


XV. MISCELLANEOUS DIENE SYNTHESES

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:

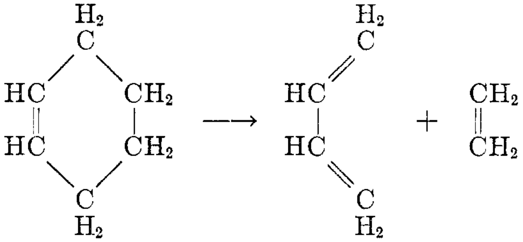


Addition occurs in a manner so that the RCO— group of the dimer is always ortho to the ring oxygen atom, and never meta (381) (for a novel example, see reference 416).

B. Reverse diene syntheses[3]

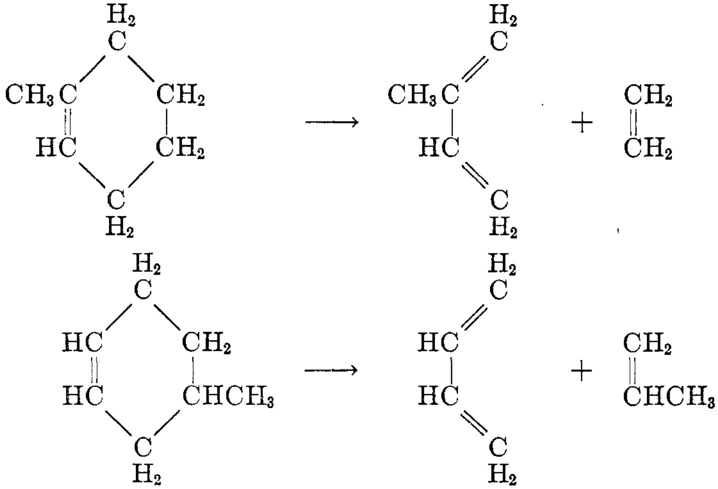
There are a number of compounds which, when heated strongly, decompose into a diene and an olefinic compound, although the diene and olefin have not been observed to recombine to give the original compound. For want of a better term, these are called reverse diene syntheses.

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



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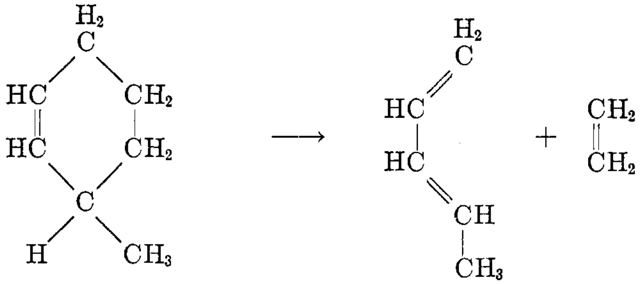
[3] Suggested by Dr. A. O. Rogers. Subsequently, Butz (411) has reversed the decomposition of cyclohexane to butadiene and ethylene.



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.

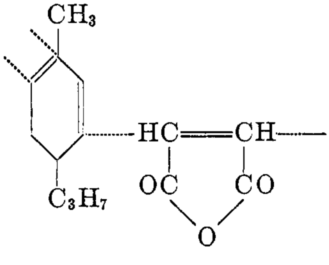
XVI. MECHANISM AND STEREOCHEMISTRY OF THE DIENE SYNTHESIS

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



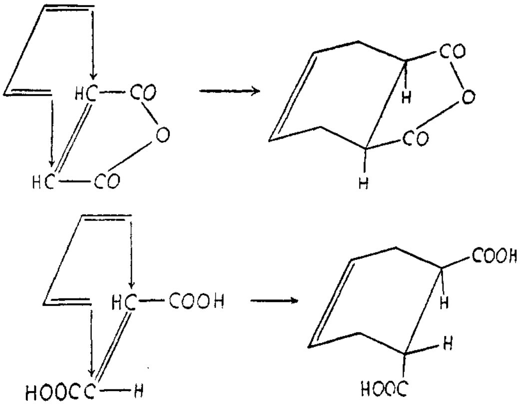
is suggested, wherein there is an alternation of terpene and maleic anhydride molecules. The significance of the dotted lines is not absolutely clear; possibly they indicate a type of coördinate linkage.

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.

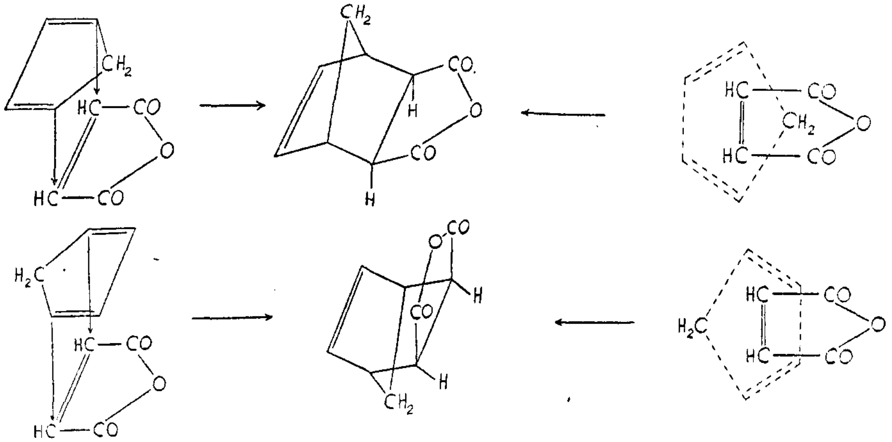
The cases of butadiene with fumaric and maleic acids are graphically illustrated below:



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

C. The general orientation scheme

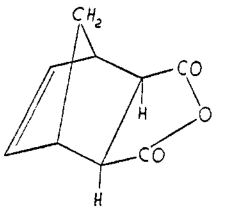
The second heading under which the stereochemical phenomena of diene syntheses may be grouped is termed "the general orientation scheme" by Alder and Stein. The question arising under this heading is whether the diene adds *cis* on one side or the other of the dienophilic double bond. Regardless of which 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:



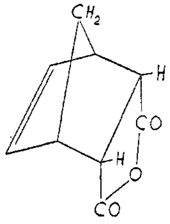
The mode of addition represented by the drawings in which the —CH_2— group of the cyclopentadiene molecule is on the same side of the dienophile molecule as are its carboxylic acid groups gives rise to an acid (I) in which the —CH_2— and carboxyl groups are also on the same side of the molecule. The 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.

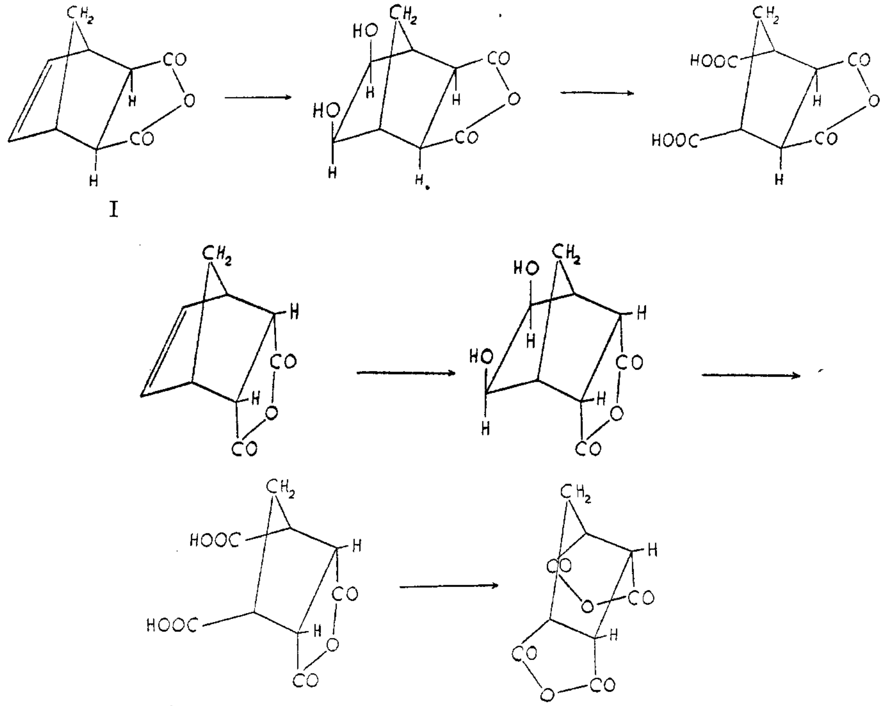


I

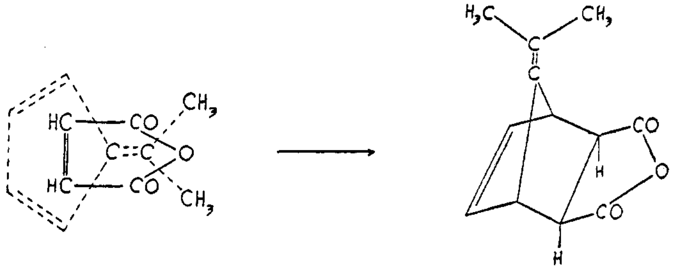


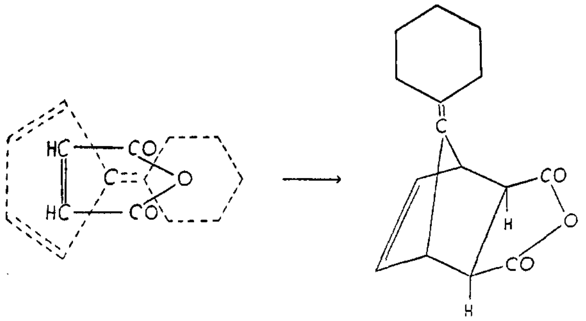
II

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:

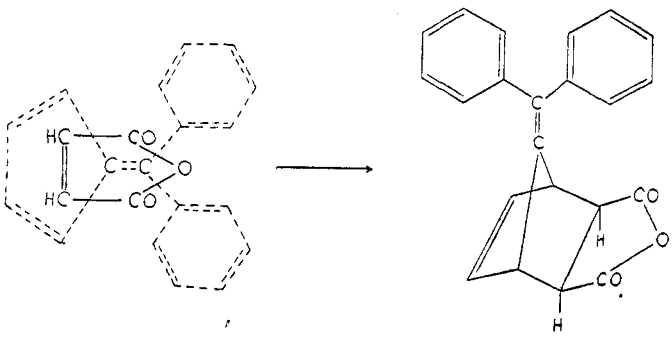


In spite of the fact that cyclopentadiene, cyclohexadiene, and similarly constituted dienes add to give adducts possessing the endo-configuration, it is well not to generalize by stating that all dienes add dienophiles to give adducts possessing the endo-configuration. A better generalization is that 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):

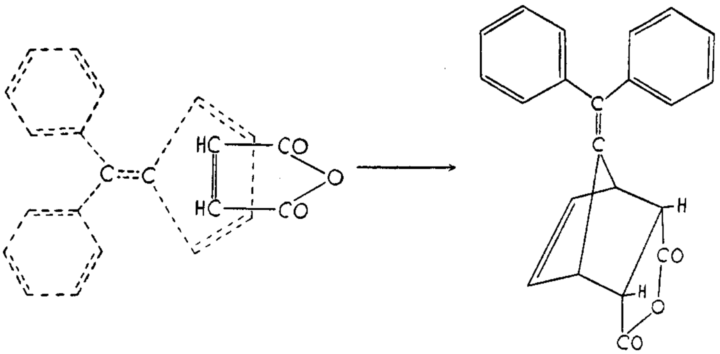




With diphenylfulvene, the double bonds of the phenyl groups are also a determining factor in the orientation of the adduct. In this case, the product is exclusively of the exo-configuration:



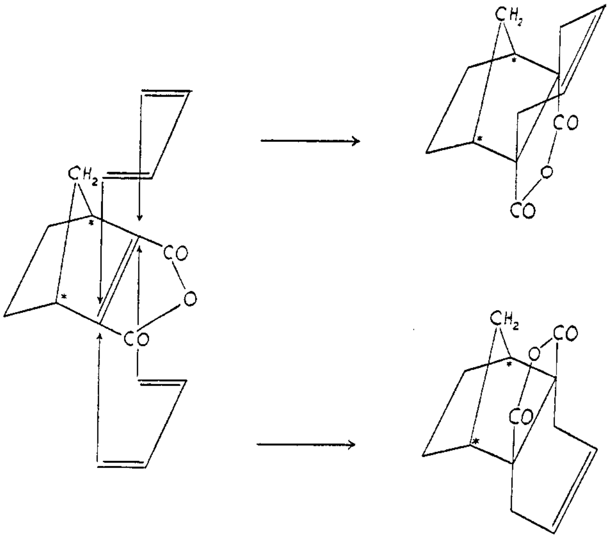
The configuration which would lead to formation of an endo-isomer is the following:



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.

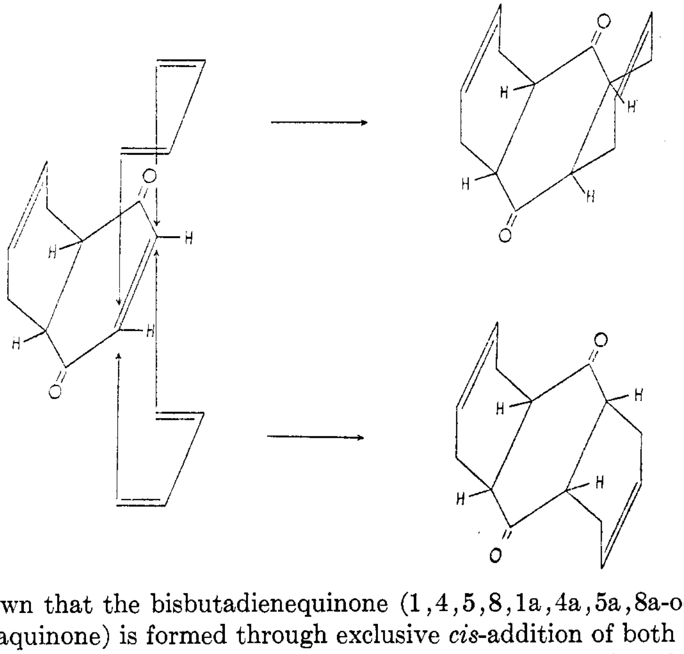
This rule of maximum accumulation of double bonds applies not only to aliphatic carbonylenic dienophiles, but also to additions to quinones, acetylenic dienophiles, diene dimerizations, etc. Thus, cyclopentadiene dimer is the endo-isomer.

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:



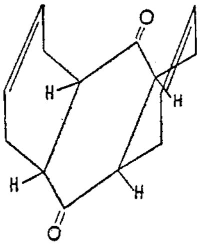
In the case cited, the addition of a diene (such as butadiene) to the adduct of 1 mole of cyclopentadiene to an acetylenic dienophile, the addition proceeds exo with respect to the methylene bridge. This appears to be generally true; while the endomethylene bridge of cyclopentadiene dimer is endo with 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.



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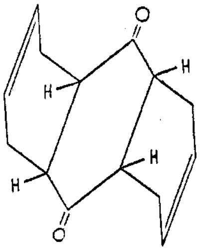
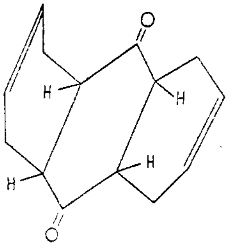
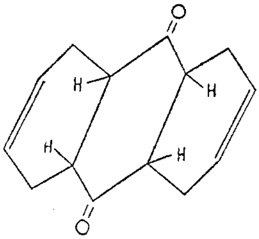


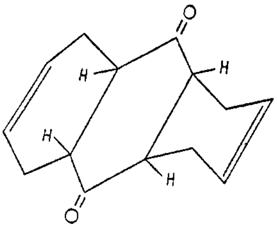
IV



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.

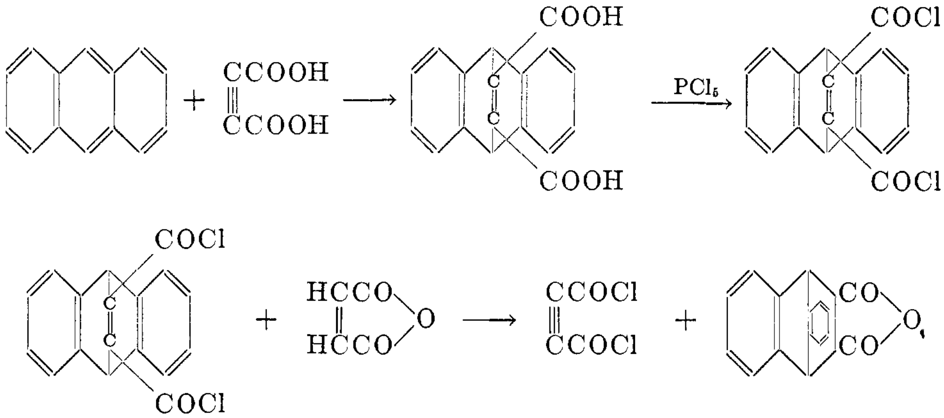
Billing (90) heated crude, gaseous maleic anhydride at 160–200°C. with terpinene, pinene, or rosin, producing resinous products. Resins from rosin and maleic anhydride have been described by Powers (304). The American Cyanamid Co. (53) has used polyterpenes.

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.

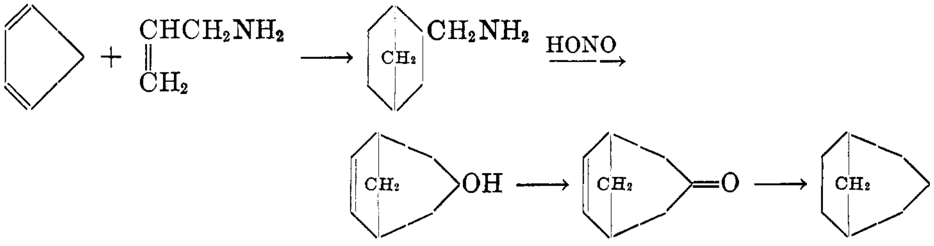
Martin, Gruse, and Lowy (292) studied the effect on gum formation in cracked petroleum distillates after dienes were removed by maleic anhydride.

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.

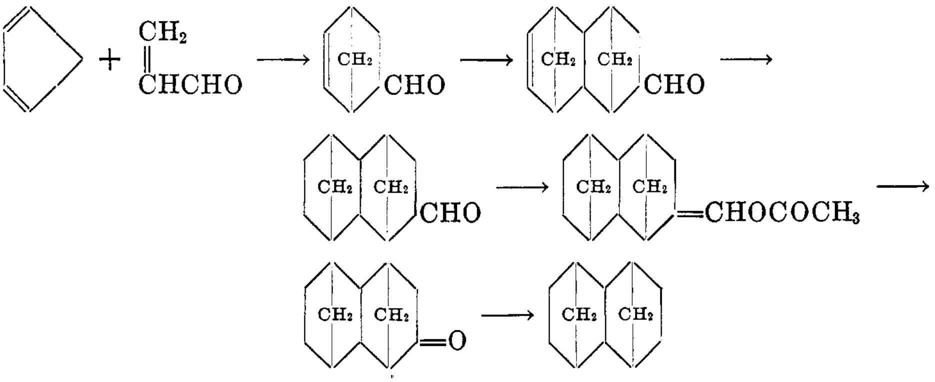
As may have been evident, the various adducts discussed in this review have shown differing degrees of heat stability, which range from the rather highly stable adducts of the simple dienes with maleic anhydride to the adducts of fulvenes and arylated anthracenes which dissociate in solution to their 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:



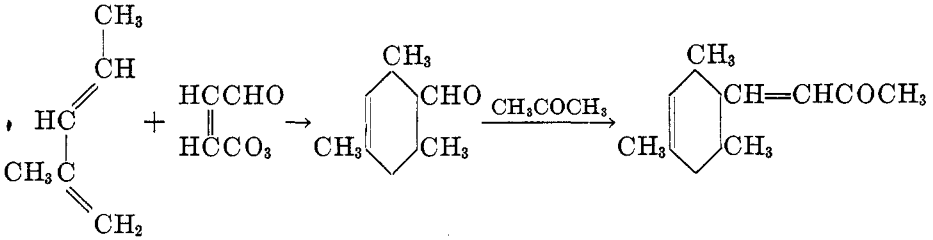
Alder and Windemuth (41, 42) used the diene synthesis in the preparation of bridged hydrocarbons. The first was bicyclo-(1:2:3)-octane, prepared by treatment of the allylamine adduct of cyclopentadiene with nitrous acid, oxidation of the resulting alcohol to the corresponding ketone, and then reduction to the hydrocarbon:



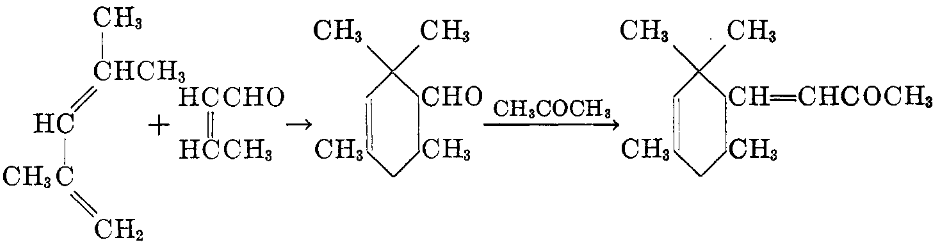
The second synthesis (42) was that of 1,4,5,8-bis(endomethylene)decalin. The acrolein adduct of cyclopentadiene was caused to add a second mole of cyclopentadiene. The resulting aldehyde was reduced and then converted into the enol acetate, oxidation of which gave a cyclic ketone. This ketone was reduced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

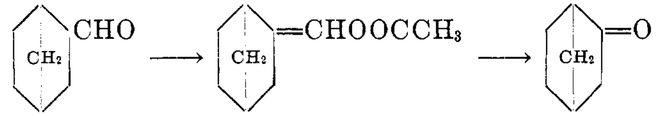


A similar product, containing an additional methyl group, was synthesized by employing 1,1,3-trimethylbutadiene in place of 1,3-dimethylbutadiene:



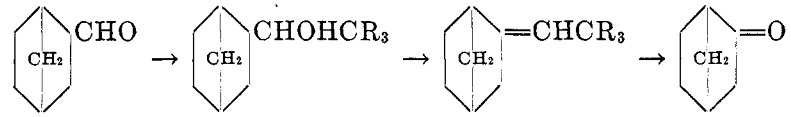
Norcamphor (144, 150) was synthesized by the reaction of acrolein with cyclopentadiene and reduction of the resulting adduct to the fully saturated aldehyde (I). The aldehyde group was eliminated and norcamphor was the end product. There are at least three ways of eliminating the aldehyde group, such 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:

(a)



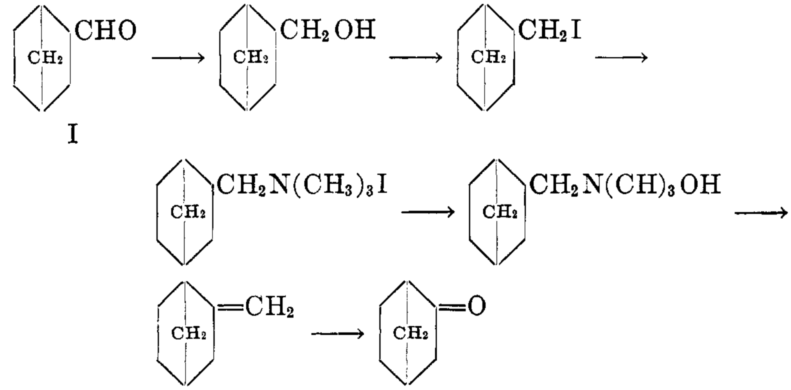
I

(b)



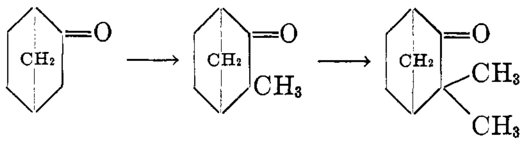
I

(c)

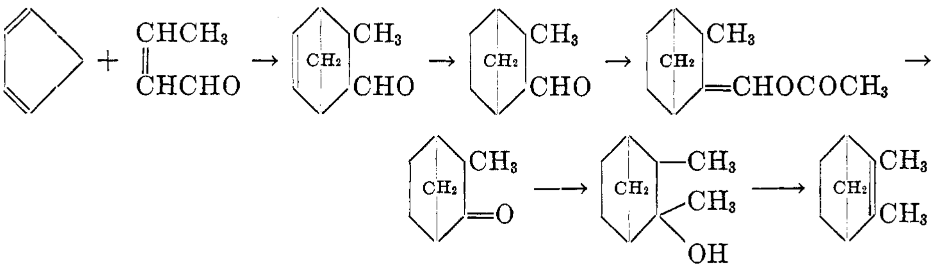


I

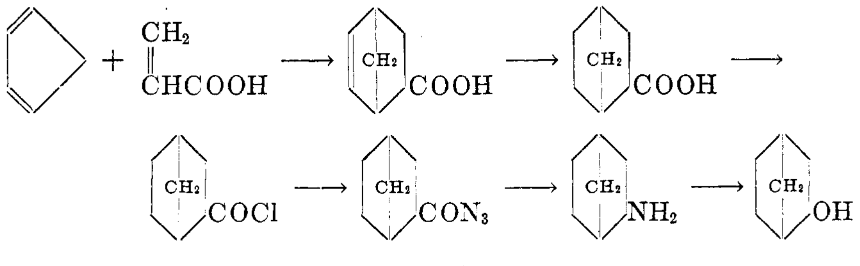
Camphenilone was synthesized from the norcamphor by double treatment with sodium amide and methyl iodide.



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.



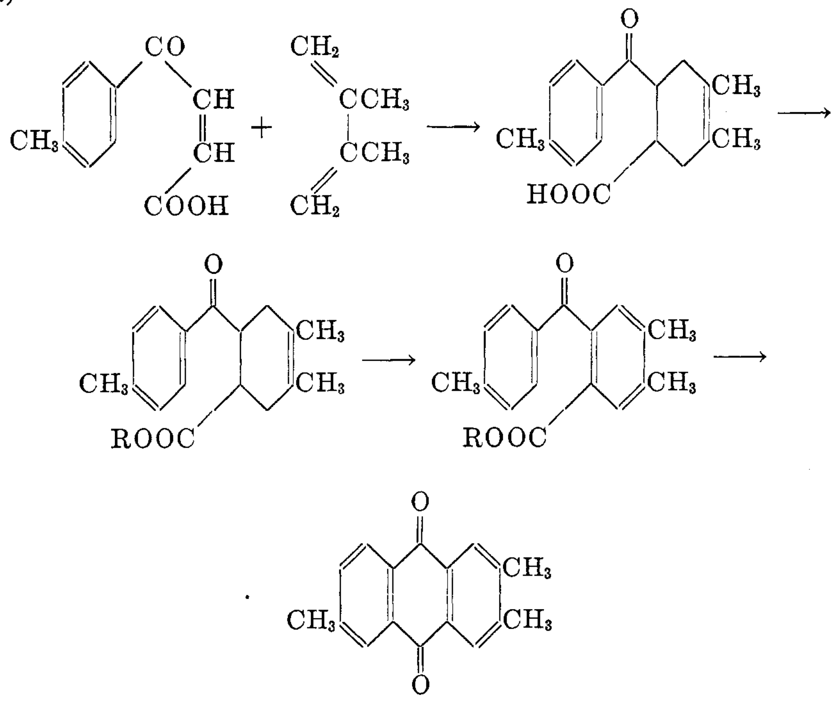
Two terpene preparations, those of *dl*-limonene and diprene, have been discussed under the heading "Dimerization". A considerable number of other preparations have been either discussed or else mentioned briefly in connection with other diene reactions. In the main, the syntheses presented in this section 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.

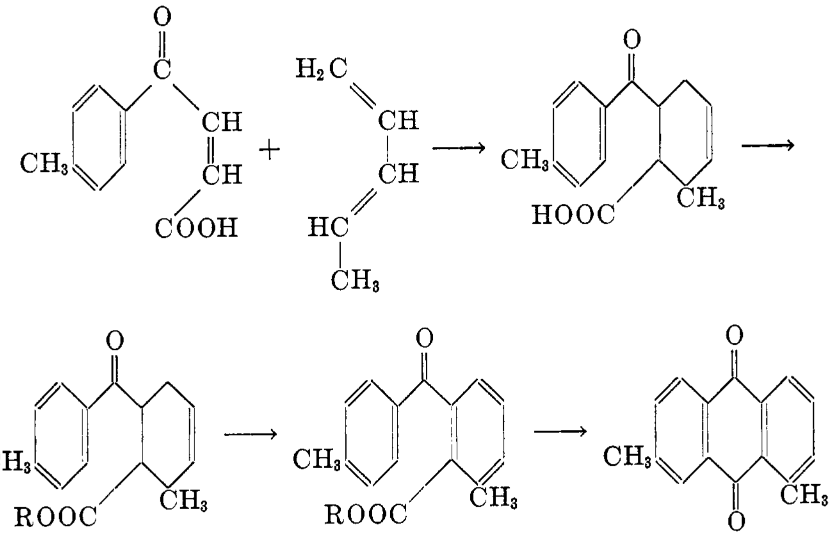
Dufraisse and Compagnon (185) synthesized rubrene from α-naphthoquinone and diphenylisobenzofuran; the diene itself was formed by a synthesis involving the diene reaction (this has been rather well covered on page 477).

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*)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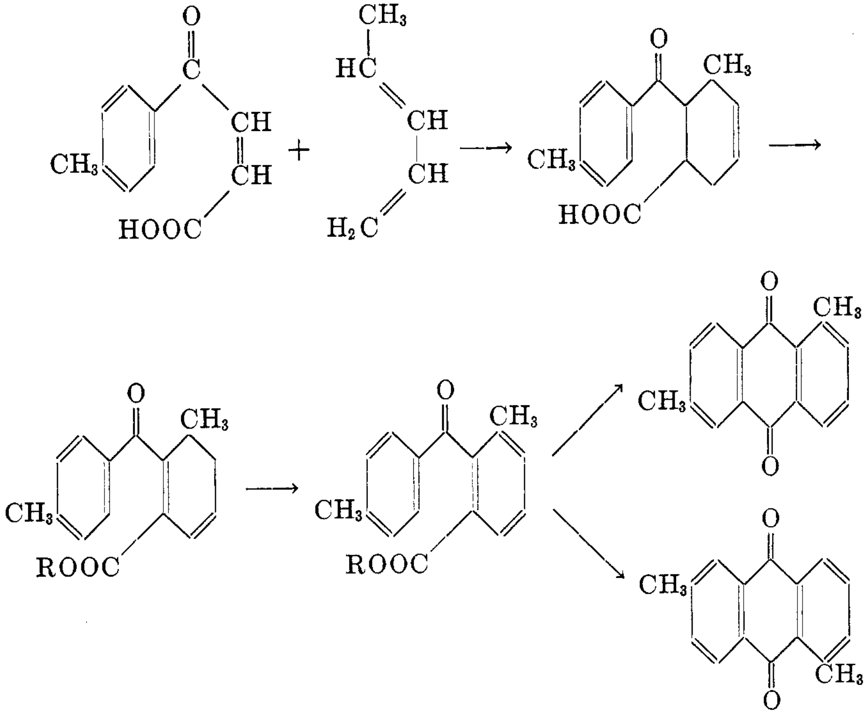
or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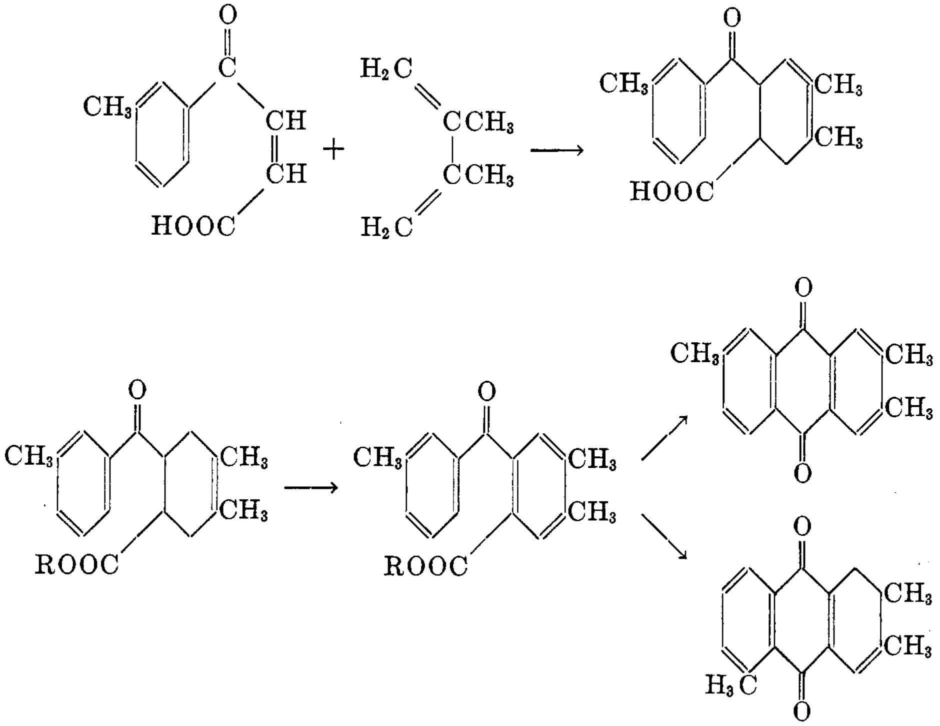
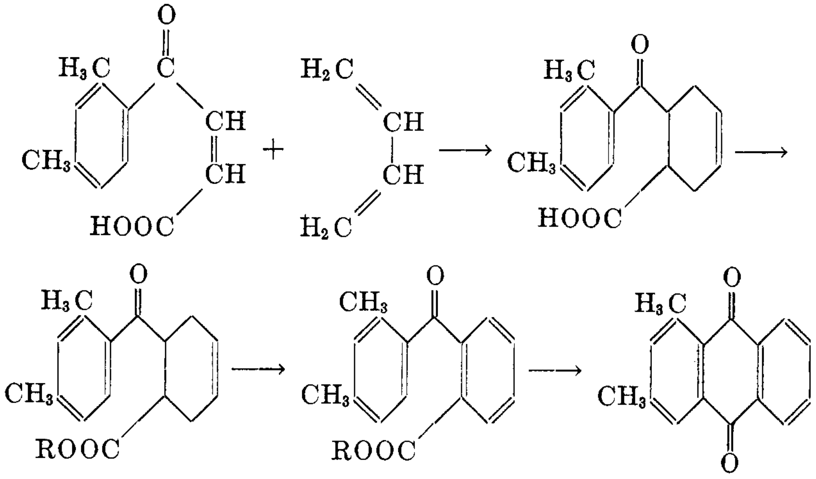
CH
H₂C
ROOC

(*c*)

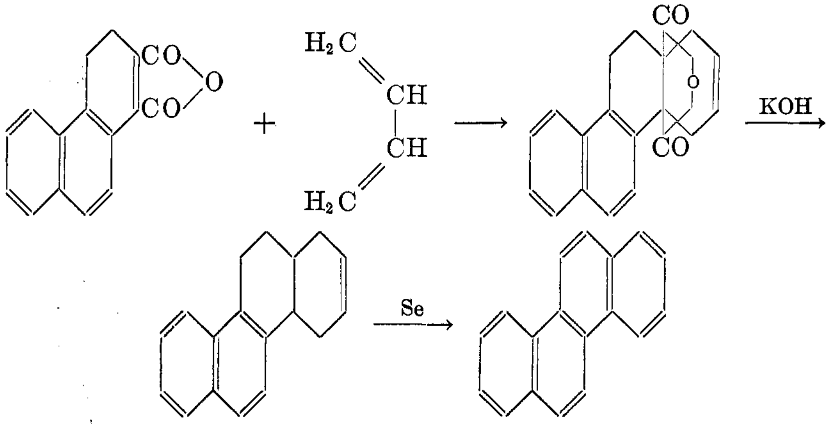


(*d*)



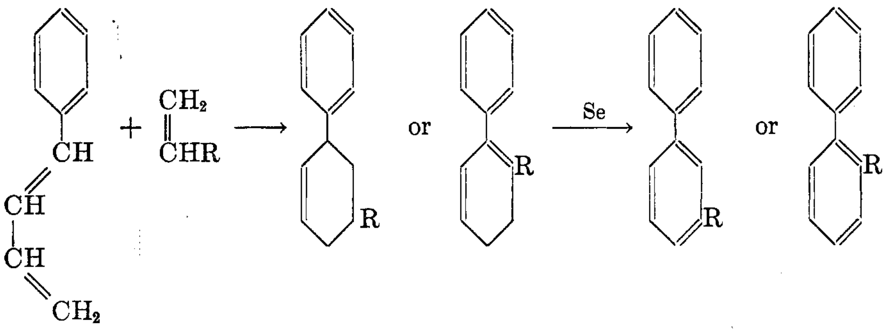
Certain of the above instances have been discussed by Fieser, Fieser, and Herschberg (213); those which they did not discuss are examples selected by the author of this review in order to show the possibilities of production of isomeric substances.

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

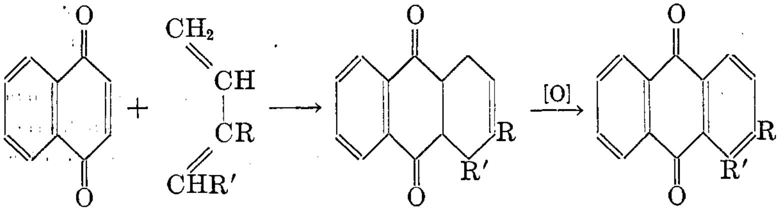


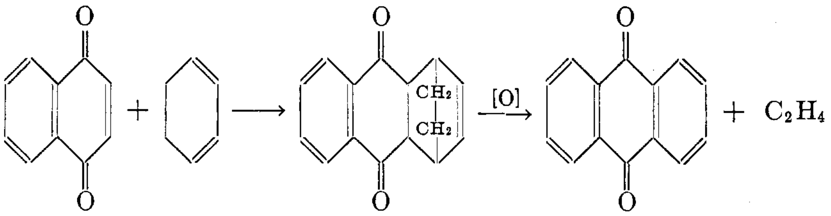
It may be seen that this method is perfectly general, for by use of the appropriate diene any desired chrysene possessing substituents in one of the external rings may be synthesized.

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.

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