

Hydrogen Fluoride Catalyzed Hydroxylation of Aromatic Compounds¹

J. A. VESELY AND LOUIS SCHMERLING

Universal Oil Products Company, Des Plaines, Illinois 60016

Received May 19, 1970

Liquid hydrogen fluoride is an effective catalyst for the hydroxylation of aromatic compounds with aqueous hydrogen peroxide at temperatures in the range of from about -30 to $+50^\circ$. For example, it catalyzes the conversion of toluene to cresol (mole ratio of *o*-cresol:*p*-cresol, about 2) and of the three xylenes to xylenols, the hydroxyl group being oriented principally in positions ortho and, to a lesser extent, para, to the methyl substituents. Hydroxylation of *tert*-butylbenzene yields only a trace of *tert*-butylphenol. The principal hydroxylation products are phenol, hydroquinone, and catechol. Hydroxylation obviously precedes loss of the *tert*-butyl group because, under the same conditions, little phenol is obtained by the reaction of benzene with hydrogen peroxide, the product being a high-melting, black, predominantly alkali-soluble resin. Surprisingly high conversion of benzene to phenol, hydroquinone, and catechol does occur when the reaction is carried out in the presence of carbon dioxide. Use of carbon dioxide also permits the hydroxylation of naphthalene to 1-naphthol, 2-naphthol, and 1,5-naphthalenediol, products which are not obtained in its absence. The HF-catalyzed reaction of phenol with hydrogen peroxide results in almost quantitative yields of hydroquinone plus catechol, the former usually predominating. The hydroxylation of other aromatic hydrocarbons and phenols is described.

The literature contains only two papers on the direct, one-step catalytic hydroxylation of aromatic hydrocarbons with aqueous hydrogen peroxide. Derbyshire and Waters² found that the reaction of mesitylene with hydrogen peroxide in sulfuric acid-acetic acid yields mesitol (2,4,6-trimethylphenol). They state that the reaction involves intermediate positive hydroxyl ions which add to the aromatic ring. However, they neither mention the yield of mesitol nor present detailed data which permit its calculation. They do say, "Since phenols are much more easily substituted than benzene, hydroxylation by $(OH)^+$ tends to produce highly oxidized product... The fact that mesitol is already substituted in all ortho and para positions to the hydroxyl group prevents its destruction by further rapid hydroxylation." This suggests that unblocked aromatic hydrocarbons, such as benzene and toluene, do not yield monohydroxylated products because such products undergo further oxidation under the experimental conditions.

Aromatic hydrocarbons (toluene and *m*-xylene) have also been oxidized by hydrogen peroxide-boron fluoride etherate reagent to produce phenols and other oxygenated products in low yield.³ For example, dropwise addition of a solution of 90% hydrogen peroxide in boron fluoride etherate to a vigorously stirred solution of *m*-xylene in methylene chloride at $10-25^\circ$ resulted in a 4% yield of 2,4-dimethylphenol and a 2% yield of 2,6-dimethylphenol, which were formed together with small amounts of 2,6-dimethylhydroquinone and 2,6-dimethyl-3-hydroxybenzoquinone. Similar reaction of toluene gave principally polymeric products with phenolic and carboxylic acidity; only a small amount (3.5%) of cresol was isolated.

A number of workers have employed peroxytrifluoroacetic acid (prepared by the reaction of trifluoroacetic acid or anhydride with hydrogen peroxide) alone^{4,5} or in the form of a boron fluoride complex⁶ as the source of positive hydroxyl for the hydroxylation of aromatic

hydrocarbons. Mesitylene, for example, gave an 88% yield of mesitol.⁶ Oxidation of phenols to quinones, but not hydroxylation to polyhydroxy compounds, was also reported.^{4,5}

It has been stated that "benzene homologs other than toluene undergo electrophilic hydroxylation on treatment with trifluoroperoxyacetic acid"⁴ and that, when hydroxylated with peroxytrifluoroacetic acid-boron fluoride, "mesitylene gave mesitol (88%)... but benzene gave only trace amounts of phenol."^{6b} It was believed that the only aromatic hydrocarbons which gave high yields of monohydroxylated product are those leading to phenols "in which positions ortho and para to the entering hydroxy group are blocked, as in case of mesitylene and isodurene, [so that] further oxidation is sufficiently slow that one can isolate the phenol in good yield."^{6b}

In the present investigation it was found that liquid hydrogen fluoride is a very effective catalyst for the hydroxylation not only of aromatic hydrocarbons, but also of phenols, with hydrogen peroxide,⁷ presumably *via* formation of positive hydroxyl ions. Even unsubstituted benzene can be hydroxylated with good yield in the presence of hydrogen fluoride under modified conditions.

Experimental Section

The aromatic compound was sealed in a 1-l. stainless steel turbomixer autoclave into which hydrogen fluoride was then charged from a tared Duraluminum bomb. The mixture was vigorously stirred while a 30% aqueous solution of hydrogen peroxide was gradually pressured in (usually during about 1 hr) from a calibrated Kel-F-lined Jerguson gauge at a rate such as to maintain the chosen reaction temperature (usually near 0° or room temperature). After all of the hydrogen peroxide had been added, the mixture was stirred for an additional 10 min or so and the hydrogen fluoride was then purged from the reactor with a stream of nitrogen for 1-2 hr prior to opening the autoclave.

The reaction product was transferred into a 1-l. Teflon beaker to which benzene gleanings from the reactor parts were subsequently added. The resulting benzene solution was carefully decanted into another Teflon beaker, in order to separate it from the small amount of accompanying aqueous acid phase which contained some benzene-insoluble product. The decanted benzene solution was treated with excess calcium carbonate to remove residual hydrogen fluoride and filtered under suction. The filtrate was usually distilled to remove benzene and unreacted aromatic compounds. The residue was either subjected to a further distillation or was extracted with aqueous alkali to yield

(1) Presented before the Division of Petroleum Chemistry at the 159th National Meeting of the American Chemical Society, Houston, Texas, Feb 1970.

(2) D. H. Derbyshire and W. A. Waters, *Nature*, **165**, 401 (1950).

(3) J. D. McClure and P. H. Williams, *J. Org. Chem.*, **27**, 24 (1962).

(4) R. D. Chambers, P. Goggin, and W. K. R. Musgrave, *J. Chem. Soc.*, 1840 (1959).

(5) J. D. McClure, *J. Org. Chem.*, **28**, 69 (1963).

(6) (a) C. A. Buehler and H. Hart, *J. Amer. Chem. Soc.*, **85**, 2177 (1963);

(b) H. Hart and C. A. Buehler, *J. Org. Chem.*, **29**, 2397 (1964).

(7) L. Schmerling, U. S. Patent 3,461,170 (1969).

alkali-soluble and insoluble segments. After acidification and ether extraction of the alkali-soluble product, it was fractionated and then characterized by nuclear magnetic resonance spectroscopy (nmr) and/or infrared spectroscopy (ir) or was submitted to preparative gas-liquid chromatography (glc) followed by identification of the peak materials by nmr and/or ir. In some cases, as with the cresols obtained from toluene or the hydroquinone-catechol mixture obtained from phenol, the composition of the residue was determined by ir with or without further distillation of the reaction product.

Benzene-insoluble product remaining in the reactor, as well as that found in the aqueous acid phase, was extracted with ether. The extract was treated with calcium carbonate to remove residual hydrogen fluoride, filtered, and then distilled to remove the ether. The bottoms were worked up by further distillation or analyzed by preparative glc and ir and/or nmr.

The most generally used quantities of reactants and catalyst in this investigation were 3-4 mol of aromatic compound, 0.29 mol (30 ml) of 30% hydrogen peroxide, and 11-12 mol of hydrogen fluoride. These quantities will be referred to hereafter as "the standard quantities."

The term "uncharacterized product" will be used in this paper to designate product which could not readily be qualitatively or quantitatively analyzed. Generally, such a product was a complex mixture of polyhydroxylated and condensation (polymerization) products and was largely alkali soluble.

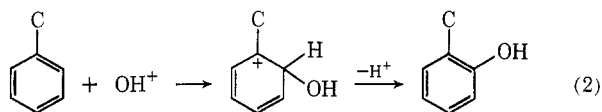
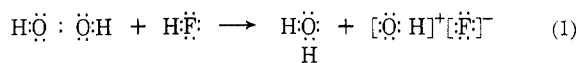
Results

Hydroxylation of Aromatic Hydrocarbons. Benzene.

—A high-melting, black, alkali-soluble resin was obtained when benzene was treated with hydrogen peroxide near 0°. The much greater reactivity of the initially formed phenol than of benzene (due to the greater solubility of phenol in the catalyst) seems to be indicated. Similar results have been reported for the reaction of benzene with peroxytrifluoroacetic acid and boron trifluoride.^{6b} Successful hydroxylation with modified hydrogen fluoride catalyst is described below.

Toluene.—Hydroxylation of toluene at near 0° resulted in a 28 mol % yield of monohydroxylated product, consisting of about 65% *o*- and 35% *p*-cresol, and a 10 mol % yield of dihydroxylated product which was shown by ir to include methylcatechol and methylhydroquinone. The latter, which predominated, was obtained in crystalline form by sublimation of the material remaining after removal of the cresol by vacuum distillation. There was also obtained a relatively large amount (about 45 wt % of the product) of higher boiling residue, most of which was quite water- and alkali-soluble, and was not further characterized; it apparently consisted of polyhydroxylated toluene and condensation products (including ethers) of hydroxylated compounds. The large amount of polyhydroxylated product probably resulted from the greater reactivity of the cresols as compared with toluene.

A possible mechanism of the reaction is shown by the following equations (eq 1 and 2). The designation OH⁺



may be an oversimplification for what might better be written (OH·H₂O)⁺ or H₃O₂⁺.

The yield of monohydroxylated toluene was increased to 49 mol % by doubling the hydrogen fluoride charge

(increasing the mol ratio of hydrogen fluoride:toluene from 2.7 to 5.3); the yield of uncharacterized alkali-soluble product (including dihydroxytoluenes) was decreased to 37 wt % of the reaction product (Table I).

TABLE I
HYDROXYLATION OF TOLUENE^a

HF, mol	H ₂ O in used catalyst, wt %	Temp, °C	Products	
			Cresols, mol %	Uncharacterized, wt %
10.8	14.8	-30	21	60
21.7	8.0	-30	32	45
10.8	14.8	0	28	46
21.0	8.2	0	49	37
10.9	14.7	30	36	42
21.2	8.1	30	52	29
10.9	14.1	55	23	57

^a Reactants: C₆H₅CH₃, 4 mol; H₂O₂, 0.39 mol; mol ratio, 10.3.

The increased amount of hydrogen fluoride had the effect of reducing the ultimate concentration of water in the catalyst phase from 15 to 8 wt %, thus prolonging the catalyst activity and resulting in increased interaction with the excess toluene present rather than with the more reactive cresol. The water includes both that added with the aqueous hydrogen peroxide and that formed by reaction of hydrogen peroxide with toluene. The former can, of course, be reduced by using hydrogen peroxide of greater strength; for example, 90% hydrogen peroxide was used in hydroxylations which are not described in this paper.

The yield of cresols was decreased to 32 mol % by carrying out the reaction with the larger amount of hydrogen fluoride at -30°. By raising the reaction temperature to 30°, the yield was increased to 52 mol % with the higher ratio of hydrogen fluoride (Table I). The yields of uncharacterized alkali-soluble product were 60 and 29 wt %, respectively. Further increase in the reaction temperature to 55° resulted in a decrease in the yield of cresols to 23 mol %, and an increase in the higher molecular weight product to 57 wt %.

Ethylbenzene.—Hydroxylation of ethylbenzene at 0° produced a 17 mol % yield of monohydroxylated product, about 88% of which was *o*-ethylphenol, the remainder being the *p*-ethyl isomer. Ethylhydroquinone was obtained in 15 mol % yield.

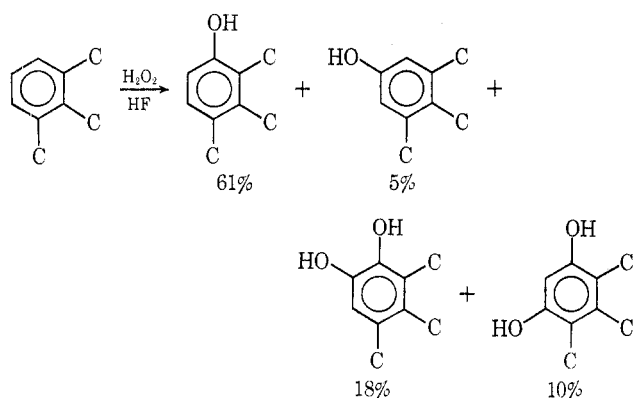
Xylenes.—*m*-Xylene was the most readily hydroxylated xylene, presumably because both methyl groups directed the hydroxyl group to the same positions. At 30°, using the standard amounts of reactants and catalyst, there was produced 46 mol % 2,4-xylenol, 8 mol % 2,6-xylenol, and 3 mol % 3,5-xylenol. The practically completely alkali-soluble uncharacterized product amounted to 30 wt % of the reaction product.

From *p*-xylene in which each unsubstituted position is ortho to one methyl and meta to the other, there was obtained a 33 mol % yield of 2,5-xylenol and 49 wt % of uncharacterized product.

o-Xylene yielded only 20 mol % monohydroxylated product, consisting of 75% 2,3-xylenol and 25% 3,4-xylenol. The yield of uncharacterized product was 69 wt %. It will be noted that, as with the other alkylbenzenes, substitution in the ortho position to an alkyl group predominated.

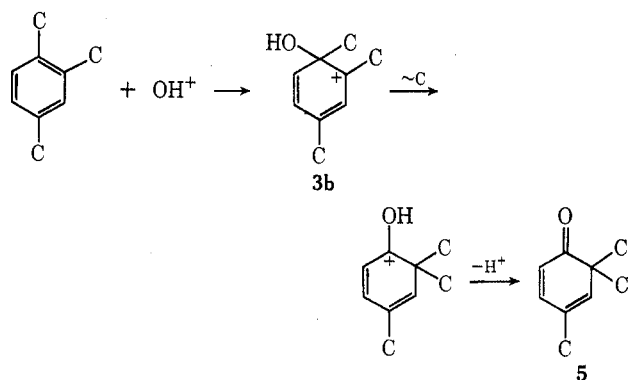
Cumene.—No monohydroxylated product was obtained when 1 mol of cumene was treated with 0.3 mol of 30% hydrogen peroxide in the presence of 12 mol of hydrogen fluoride at 0°. The reaction product was an alkali-soluble black tar. It seems probable that the hydrogen attached to the tertiary carbon atom of the cumene was involved in the reaction by being abstracted by an ion (a positive hydroxyl ion or an isopropyl cation) to yield a benzylic carbonium ion which underwent further condensation reactions.

Hemimellitene.—Hemimellitene (1,2,3-trimethylbenzene) was hydroxylated at room temperature with the production of 61 mol % 2,3,4-trimethylphenol, 5 mol % 3,4,5-trimethylphenol, 18 mol % 3,4,5-trimethylcatechol, and 10 mol % 4,5,6-trimethylresorcinol, in addition to a relatively small amount of unidentified products. All four products were products of normal hydroxylation with substitution in ortho and/or para positions.

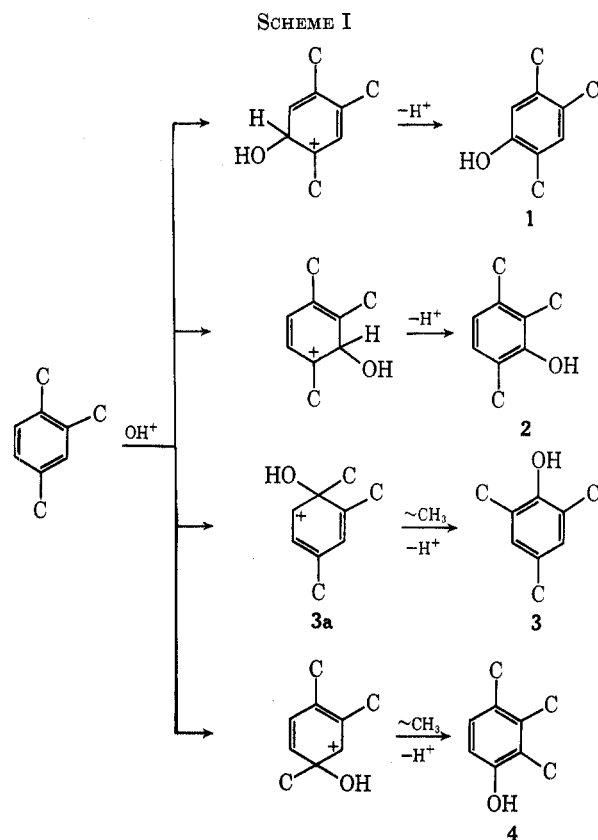


Pseudocumene.—Hydroxylation of pseudocumene (1,2,4-trimethylbenzene) at about 0° gave a 58 mol % yield of monohydroxylated derivatives in addition to higher boiling uncharacterized products. The major products were the expected 2,4,5-trimethylphenol (1, 21 mol % yield) and 2,3,6-trimethylphenol (2, about 16 mol % yield). There were also obtained 2,4,6-trimethylphenol (3, 14 mol % yield) and 2,3,4-trimethylphenol (4, about 7 mol % yield), formation of which involved a methyl shift accompanying the hydroxylation. Scheme I suggests a possible mechanism of the hydroxylation.

Elimination of a proton from a tertiary canonical form (3b) of the secondary ion (3a) results in the production of a cyclohexadienone (5).⁸ Alternatively, 5 may

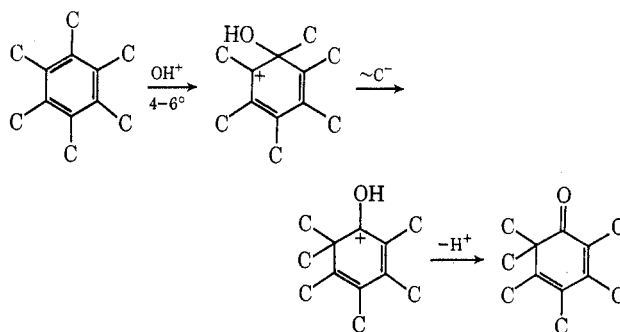


(8) A homolog of 5 was isolated by Hart and Buehler^{6b} from the product of the reaction of prehnitene (1,2,3,4-tetramethylbenzene) with peroxytrifluoroacetic acid. The alternate methyl shift also occurred, yielding 2,3,4,6-tetramethylphenol.



be considered to form from 3a → 3b (cf. 6b). Further reaction of 5, particularly with phenolic compounds present in the reaction mixture, yields "uncharacterized product." It was noted during the course of the present investigation that a methyl shift occurred only when the methyl group was in para position to an alkyl or hydroxyl group.

Hexamethylbenzene.—A cyclohexadienone was the chief product of the hydroxylation of hexamethylbenzene near 0°. Instead of displacement of a methyl group with the production of pentamethylphenol, methyl shift occurred, resulting in an 80 mol % yield of 2,3,4,5,6,6-hexamethyl-2,4-cyclohexadienone.⁹ Formation of this dienone is explained by a mechanism analogous to that shown above for the formation of 5. The high yield of the dienone may be attributed to its un-



(9) This product was also obtained in good yield by the reaction of hexamethylbenzene with peroxytrifluoroacetic acid-boron fluoride.¹⁰ That obtained in the present investigation had properties in excellent agreement with those of the earlier product. The nmr spectrum consisted of three signals, τ 8.92, 8.19, and 8.02, with relative areas of 2:3:1. The molecular weight found by mass spectroscopy was 178. *Anal.* Calcd for C₁₅H₁₈O: C, 80.85; H, 10.18. Found: C, 80.45; H, 10.22.

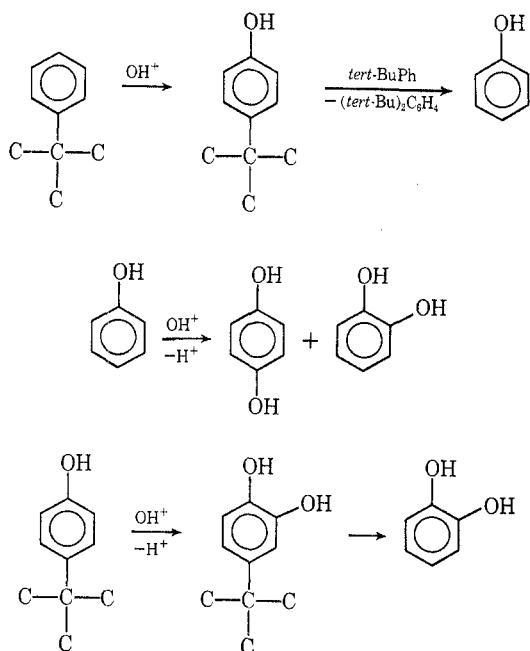
(10) H. Hart, P. M. Collins, and A. J. Waring, *J. Amer. Chem. Soc.*, **88**, 1005 (1966).

usual stability under acid conditions because of its high methyl content.

Mesitylene.—Hydroxylation of mesitylene (1,3,5-trimethylbenzene) was not accompanied by methyl shift. Using the standard amounts of reactants at 0°, mesitol was obtained in 74 mol % yield, together with a 25 mol % yield of dihydroxymesitylene (2,4,6-trimethylresorcinol). Both products were shown by ir to be substantially free of isomers.

tert-Butylbenzene.—Only a trace of *tert*-butylphenol was obtained when *tert*-butylbenzene was treated with hydrogen peroxide at about 0° in the presence of hydrogen fluoride. The chief products were phenol (30 mol % yield), hydroquinone (35 mol %), and catechol (13 mol %). Very little uncharacterized alkali-soluble material was formed. Since phenol is not formed from benzene under these conditions, it is obvious that the hydroxylation must have preceded or occurred simultaneously with the loss of the *tert*-butyl group.

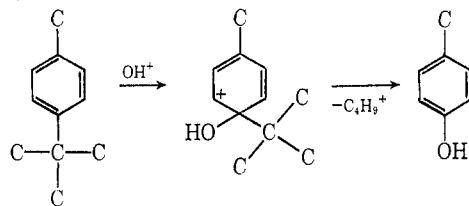
The preponderance of hydroquinone over catechol seems to indicate that the dihydroxy compounds were formed mainly by hydroxylation of phenol (see below), the *tert*-butyl group being eliminated before the second hydroxyl group was introduced.



***p*-tert-Butyltoluene.**—*p*-*tert*-Butyltoluene produced isomeric cresols (33% *o*- and 67% *p*-cresol) but in only 7 mol % yield, together with 82 wt % of uncharacterized alkali-soluble material. Considerable conversion of the *p*-*tert*-butyltoluene to 3,5-di-*tert*-butyltoluene occurred. This compound was characterized by ir and nmr. Its boiling point (228°) and melting point (31–32°) are in agreement with those reported for the compound prepared by the reaction of *tert*-butyl chloride and toluene in the presence of aluminum chloride (bp 227.5–228° and mp 31.5–32°).¹¹

The fact that the *p*-cresol predominated indicates that it was not formed exclusively by hydroxylation of toluene and suggests that much of the cresol was prob-

ably formed by displacement of the *p*-*tert*-butyl group by the hydroxyl ion.



Effect of Carbon Dioxide on Hydrocarbon Hydroxylation.—A search for a modified procedure which would permit the monohydroxylation of benzene by increasing its solubility in the catalyst led to carrying out the hydroxylation under carbon dioxide pressure.¹² The reaction near 0° of 3 mol of benzene with 0.3 mol of hydrogen peroxide in the presence of 14 mol of hydrogen fluoride and 2 mol of carbon dioxide (31% by weight of the catalyst) yielded 37 mol % phenol, 16 mol % catechol, and 37 mol % hydroquinone. Only 8 wt % of uncharacterized product was formed.

This striking effect of the carbon dioxide was similarly shown in the hydroxylation of cumene. Reaction at 4–10°, using the standard amounts of reactants and catalyst together with 41% of carbon dioxide by weight of the catalyst resulted in a 12 mol % yield of *o*-isopropylphenol, 9 mol % *p*-isopropylphenol, and 52 mol % of dihydroxylated compounds. The latter apparently consisted chiefly of 2,4-dihydroxyisopropylbenzene (4-isopropylresorcinol) together with minor amounts of 3,4 and 2,5 isomers (4-isopropylcatechol and isopropylhydroquinone).

The composition of the dihydroxy product indicates that orientation of the second hydroxyl group was influenced more by the isopropyl group than by the hydroxyl already present. The uncharacterized phenolic product represented about 30 wt % of the reaction product; it showed that it was composed chiefly of higher phenolic condensation products.

The highly beneficial effect of carbon dioxide was also demonstrated in the hydroxylation of naphthalene. In the absence of carbon dioxide, the product consisted only of high-melting, black, alkali-soluble resinous material. In the presence of carbon dioxide (22% by weight of the catalyst) naphthalene was converted at 4–11° to 30 mol % 1-naphthol, 9 mol % 2-naphthol, and 17 mol % 1,5-naphthalenediol, in addition to small amounts of other isomeric diols and a substantial amount (about 35 wt % of the product) of higher boiling materials.

Carbon dioxide also increased the yield of cresols obtained from toluene. At 0° with a mol ratio of hydrogen fluoride:toluene of 3.8 and with 42% carbon dioxide by weight of the hydrogen fluoride, cresol (2.3 *o*:-*p*-ratio) was obtained in 49 mol % yield (compared to 28 mol % in the absence of carbon dioxide). With about double the amount of hydrogen fluoride (moles of hydrogen fluoride:moles of toluene, 7.0) and 35% carbon dioxide by weight of the hydrogen fluoride, the cresols (2.1 *o*:-*p*-ratio) were obtained in 67 mol % yield (compared to 48 mol % in the absence of carbon dioxide).

(11) R. deCapeller, *Helv. Chim. Acta*, **11**, 166 (1928); *Chem. Abstr.*, **22**, 1339 (1928).

(12) J. A. Vesely and G. L. Hervert, U. S. Patent 3,453,332 (1969).

That the carbon dioxide pressure favors the formation of monohydroxylated aromatic hydrocarbons is confirmed by the results obtained with mesitylene. As mentioned above, under the standard conditions at near 0°, mesitol and dihydroxymesitylene were obtained in 74 and 25 mol % yields, respectively. Carrying out the reaction in the presence of carbon dioxide (about 50% by weight of the hydrogen fluoride) resulted in 92 mol % of mesitol and 8 mol % of the dihydroxymesitylene.

The carbon dioxide also had another desirable effect on the hydroxylations. It acted as an internal coolant, making more rapid addition of the hydrogen peroxide possible without an accompanying excessive rise in reaction temperature.

Hydroxylation of Phenols.—Oxidation to quinones rather than hydroxylation to polyhydric phenols usually occurs when monohydric phenols are contacted with hydrogen peroxide under conditions suitable for rapid reaction. Treatment of an acetic acid solution of a phenol (phenol, *o*-, *m*-, and *p*-cresol, *tert*-butylphenol or thymol) with 30% aqueous hydrogen peroxide for a prolonged period ("a week or two") at room temperature or 2 or 3 days at 60° produced unspecified quantities of polyhydric phenols (respectively hydroquinone plus "a little" catechol, methylhydroquinone, methylhydroquinone, 4-methylcatechol, 2,3,4,5-tetrahydroxy-*tert*-butylbenzene, and tetrahydroxy-*p*-cymene) as well as quinones.¹³ Dilute solutions (1–10%) of hydrogen peroxide, with added ferrous sulfate, have been used for the oxidation of phenol during 24 hr at room temperature to chiefly hydroquinone and catechol.¹⁴

On the other hand, the acid-catalyzed hydroxylation of phenols by hydrogen peroxide does not seem to have been described, presumably because the oxidation to quinones predominated. The reaction of some phenols (*o*- and *m*-cresol and 2,3-dimethylphenol) with peroxytrifluoroacetic acid gives only resins while others (*m*- and *p*-xylenols and 2,3,5-trimethylphenol) give 50–80% yields of quinones.⁴ Hydrogen fluoride catalyzes the practically instantaneous hydroxylation of phenols in good yield, particularly at 0–30°.

Phenol.—Phenol was readily converted in excellent yield to a mixture of hydroquinone and catechol, the former predominating. Thus, at room temperature with the standard phenol:hydrogen peroxide ratio of 10.3, hydroquinone was obtained in 52 mol % yield and catechol in 35 mol % yield; the hydroquinone:catechol mol ratio was 1.5. Changing the ratio of reactants resulted in the yields shown in Table II.

TABLE II

$$\text{C}_6\text{H}_5\text{OH} + \text{H}_2\text{O}_2 \xrightarrow[20-30^\circ]{\text{HF}} \text{C}_6\text{H}_4(\text{OH})_2$$

Expt	PhOH:H ₂ O ₂ mol ratio	Yields, mol %			Unknown, wt %
		Hq ^a	Cat ^b	Hq:Cate	
1	20	54	42	1.3	<5
2	10	52	35	1.5	<7
3	3.4	50	34	1.5	12
4	1.1	35	17	2.1	31

^a Hydroquinone. ^b Catechol.

- (13) G. G. Henderson and R. Boyd, *J. Chem. Soc.*, **97**, 1659 (1910).
 (14) (a) O. Y. Magidson and N. A. Preobrazhenski, *Trans. Sci. Chem. Pharm. Inst. (Moscow)*, **16**, 65 (1926); *Chem. Abstr.*, **23**, 1630 (1929). (b) H. Goldhammer, *Biochem. Z.*, **189**, 81 (1927); *Chem. Abstr.*, **22**, 767 (1928). (c) A. Chwala and M. Pailer, *J. Prakt. Chem.*, **152**, 45 (1939).

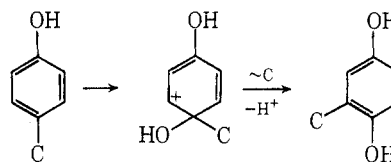
It will be noted that the uncharacterized alkali-soluble product increased as the ratio of phenol to hydrogen peroxide decreased. The higher conversion of phenol compared to toluene is undoubtedly due to the greater solubility of phenol in the catalyst. It was found that 95 parts by weight of phenol are soluble in 5 parts by weight of hydrogen fluoride.

Cresols.—3-Methylcatechol (15 mol % yield) and about 50 mol % of methylhydroquinone were produced by the hydroxylation of *o*-cresol at room temperature. More of the latter product was present in the largely uncharacterized alkali-soluble product. Preference for hydroxylation at the carbon atom in ortho or para position to the hydroxyl group rather than to the methyl group is evident. Also, para orientation is preferred over ortho in substitution in phenols.

At about 30°, *m*-cresol reacted with hydrogen peroxide yielding 33 mol % (chiefly) 4-methylcatechol and 63 mol % methylhydroquinone in addition to a small amount of uncharacterized material (about 10 wt % of the product). The mol ratio of the methylhydroquinone:methylcatechol was 1.9.

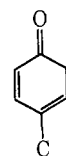
The product obtained by the hydroxylation of *p*-cresol at 0° using the standard amounts of reactants included 41 mol % 4-methylcatechol, 20 mol % methylhydroquinone, and 13 mol % of 2,2'-dihydroxy-5,5'-dimethylbiphenyl ("2,2'-di-*p*-cresol").

The formation of methylhydroquinone is significant. Since the recovered, unreacted, cresol contained no isomers, it is certain that the formation of the methylhydroquinone involved a methyl shift during the hydroxylation.



The identity of the "dicresol" was indicated by its melting point (153–154°, which is the same as that cited in Beilstein) and confirmed by nmr. Its formation probably involved the intermediate formation of 4-methyl-2,4-cyclohexadienone which underwent ionic or free-radical dimerization. This dimer has been obtained by a number of investigators by oxidation of *p*-cresol in alkaline solution with potassium ferricyanide, ferric chloride, or Fenton's reagent (FeSO₄ + H₂O₂).¹⁵

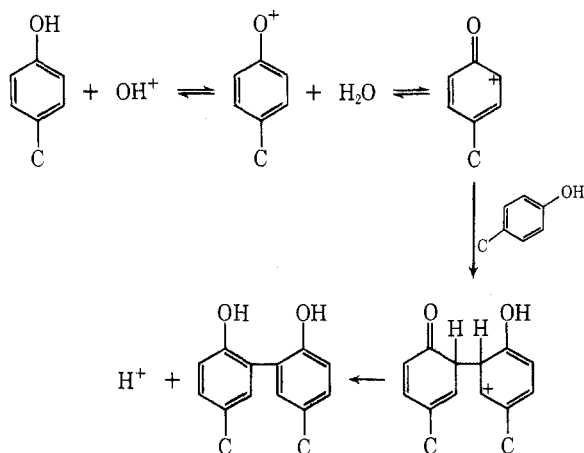
It was concluded by earlier workers,¹⁵ without giving a detailed mechanistic scheme, that the oxidation of the cresol involved the formation of a cyclohexadienone free radical which then dimerized.



However, under the present conditions, it appears more probable that a methylcyclohexadienonyl cation

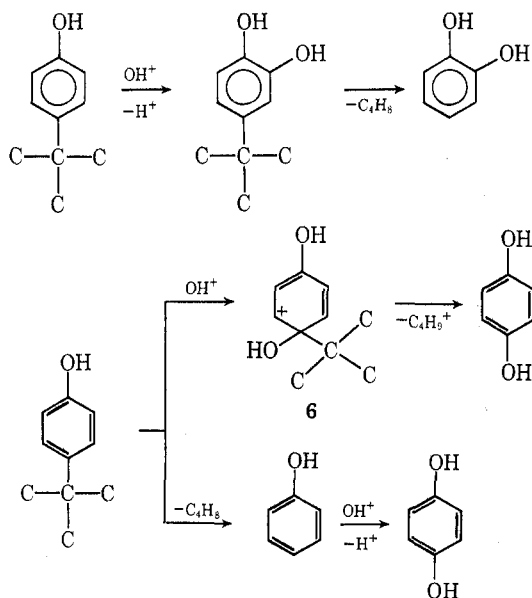
- (15) S. L. Cosgrove and W. A. Waters, *J. Chem. Soc.*, 1726 (1951).

was involved in a condensation reaction with *p*-cresol.

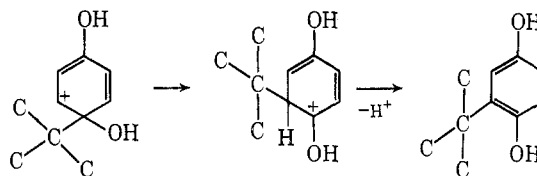


Butylphenols.—The reaction of 0.33 mol of *p*-*sec*-butylphenol with 0.1 mol of hydrogen peroxide in the presence of hydrogen fluoride at -15 to -12° yielded 18 mol % hydroquinone, 42 mol % *sec*-butylcatechol, and about 3 mol % phenol, together with much uncharacterized product (63.5 wt %). Catechol may have been present but was not detected by ir analysis due to the presence of masking bands. The relatively large amount of uncharacterized product may have been due largely to the usual type of side reactions (including conversion to a cyclohexadienone). It was probably due also to the presence of a hydrogen atom attached to the tertiary benzylic carbon atom of *sec*-butylbenzene.

Near -15° , *p*-*tert*-butylphenol yielded 52 mol % catechol, 19 mol % *tert*-butylcatechol, 7 mol % hydroquinone, and uncharacterized material amounting to about 43 wt % of the reaction product. No phenol was obtained. The high yield of catechol again shows (as in the case of *tert*-butylbenzene or *p*-*tert*-butyltoluene) that most of the reaction involves addition of hydroxyl before elimination of the *tert*-butyl group.



At 0° , *p*-*tert*-butylphenol reacted with hydrogen peroxide to yield 15 mol % catechol, 34 mol % *tert*-butylcatechol, 8 mol % hydroquinone, 2 mol % *tert*-butylhydroquinone, 9 mol % phenol, and ~ 31 wt % of uncharacterized product. The ratio of catechols to hydroquinones was 4.7, which was about one-half the ratio (10.1) obtained in the near -15° reaction temperature. Formation of *tert*-butylhydroquinone occurred by way of rearrangement of the butyl group by action of the hydroxyl group.



Dihydric Phenols.—Both catechol and hydroquinone reacted with hydrogen peroxide at 24 – 30° to produce complex mixtures which contained some tri- and tetrahydroxybenzenes, hydroxydiphenyl ethers, hydroxydibenzodioxanes, and other compounds. No pure products could be isolated.

Resorcinol, on the other hand, was readily converted to trihydroxybenzenes. At room temperature, it produced an 89 mol % yield of hydroxyhydroquinone and a 6 mol % yield of pyrogallol (mol ratio, 14). At near 0° , the yields of hydroxyhydroquinone and pyrogallol were 69 and 10 mol %, respectively (mol ratio, 7). The good results with resorcinol may be due to the fact that it does not oxidize to quinones as do catechol and hydroquinone. It may be the further reaction of these quinones which is in part responsible for the complex mixture of high-molecular-weight product obtained by the reaction of catechol and hydroquinone with hydrogen peroxide. Also, as in the case of *m*-xylene, both substituents in resorcinol direct to the same positions.

Effect of Carbon Dioxide on Phenol Hydroxylation.

Carbon dioxide has a less marked effect on the reaction of hydrogen peroxide with phenols than with aromatic hydrocarbon, chiefly because the solubilities of the phenols in the catalyst are already high and result in high conversions to hydroxylated product, even in the absence of carbon dioxide. Because carbon dioxide acts both as solubilizer and as an internal coolant, its use again makes possible a faster rate of addition of the peroxide without the normally observed temperature increase. It also has the advantage that in its presence the amount of hydrogen fluoride may be decreased (cut in half) without decreasing the yield of hydroxylation product.

Registry No.—Toluene, 108-88-3; ethylbenzene, 100-41-4; *m*-xylene, 108-38-3; *p*-xylene, 106-42-3; *o*-xylene, 95-47-6; cumene, 98-82-8; hemimellitene, 526-73-8; pseudocumene, 95-63-6; hexamethylbenzene, 87-85-4; mesitylene, 108-67-8; *tert*-butylbenzene, 98-06-6; *p*-*tert*-butyltoluene, 98-51-1; phenol, 108-95-2; *o*-cresol, 95-48-7; *m*-cresol, 108-39-4; *p*-cresol, 106-44-5; *p*-*sec*-butylphenol, 99-71-8; *p*-*tert*-butylphenol, 98-54-4; resorcinol, 108-46-3.