Alkylation of Phenols. II. The Selective Formation of Thymol from *m*-Cresol and Propylene with a γ-Alumina Catalyst

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The alkylation of *m*-cresol with propylene was carried out over a γ-alumina catalyst in a flow system under atmospheric pressure. It was found that the composition of the thymol mixture thus obtained was greatly *ortho*-rich. It was also observed that the catalytic activity varied with the temperature and the atmosphere for the calcination of the catalyst, whereas the selectivity for thymol formation was almost constant at about 90% at the reaction temperature of 250 °C. It has been established that thymol can be obtained selectively by vapor-phase alkylation over a commercial γ-alumina catalyst under appropriate reaction conditions. Furthermore, the active sites of γ-alumina for this reaction were investigated by the poisoning technique with acids and bases. It was suggested that, for the alkylation, the Lewis-acid sites (surface aluminum) and the adjacent acid sites (surface hydroxyl) are necessary. The mechanism of the alkylation on those sites is also discussed.

In the first part of this series the present authors reported their results on the vapor-phase alkylation of *m*-cresol with propylene over supported metal sulfate catalysts.[1] It was shown that the activity of the catalyst depended on the catalyst acidity, and that the selectivity of the catalyst for thymol formation seemed to be affected by the surface structure of the catalyst. However, experimental research to obtain thymol in higher yields has been required, because thymol is the raw material of an important perfumery, menthol.

On the other hand, it is well known that γ-Al_2O_3 has acidity[2-5] and promotes the reaction of phenol with alcohols;[6,7] recently the structure and orientation of phenols chemisorbed on γ-Al_2O_3 have been reported.[8] No method of synthesizing thymol using this catalyst is found in the literature. It is, therefore, of particular interest to examine the activity and selectivity of γ-Al_2O_3 for the said reaction.

The present paper will describe the results on the γ-Al_2O_3 catalyst, which shows quite a good thymol selectivity. Descriptions will also be given of the active sites of the catalyst for the alkylation, as well as discussions of the reaction mechanism.

Experimental

Materials. Commercial *m*-cresol was vacuum-distilled under an atmosphere of nitrogen; the purity was estimated to be over 99.5% by means of gas chromatography. Propylene, with a purity of over 99%, was obtained from the Mitsubishi Petrochemical Co., Ltd.

Catalyst. AE-11-type γ-Al_2O_3 obtained from the Nishio Industries Co., Ltd., was used. The alumina was pellected, crushed, and sized in 10—20 mesh, and then it was heat-treated before reaction at a temperature between 250 and 900 °C for 3 hr in an atmosphere of nitrogen, oxygen, hydrogen, or air. When the calcination temperature was below 500 °C, the catalyst was heated in a glass tube reactor, while when it was above 500 °C, it was calcined in a crucible in the air.

Analysis. The liquid products obtained were analyzed by gas chromatography (GC) and identified by a comparison of their chromatograms with those of authentic samples. The conditions for the analysis have been described in a previous report (Part I).[1] The analysis of the gaseous products was done by another GC with a column containing DMF on Chromosorb AW (8 m, 0 °C).

Measurement of the Surface Properties. The surface acidity of the catalyst was determined by the usual titration method with *n*-butylamine and Hammett indicators and by the color change of *p*-phenylenediamine.[9] The specific surface area of the catalyst was measured by the BET method using the N_2 adsorbate. The X-ray powder diffraction patterns of the catalyst was taken using filtered copper $K\alpha$ radiation.

Apparatus and Procedure. The same continuous-flow apparatus as has been described in Part I was used. The reaction was carried out in the same manner as has been described in Part I. In the experiments to investigate the poisoning effect of the acid or base agent, the reagent was introduced into the catalyst bed before the reaction. After the injection, the carrier gas was made to flow for 30 min; the alkylation reaction was then carried out.

The activity of the catalyst was expressed in terms of the conversion of *m*-cresol; it was taken at the highest conversion, which usually occurred after 1 or 2 hr of process time.

The selectivity of the catalyst defined as below did not change with the process time, except at the start of the reaction:

$$\text{Selectivity} = \frac{\text{thymol}}{(\text{thymol isomers}) - (\text{unknown})} \times 100\ (\%)$$

Results and Discussion

The material balance of the reaction of *m*-cresol and propylene was first investigated at the reaction temperature of 250 °C using γ-Al_2O_3 calcined at 300 °C in an N_2 stream. Over 90% of the reacted propylene was obtained in the form of alkylates. All of the *m*-cresol was recovered in the liquid product. Some of the lost propylene would be consumed by the polymerization and cracking to produce other hydrocarbons. Practically, propane was detected in the exhaust gas. The products obtained in this alkylation, except at higher reaction temperatures, are as follows:

The influence of *iso*-thymol on the results below 300 °C could be neglected because its amount almost held constant at about 2% of all the alkylates. There was also an unknown peak at the end of the gas chromatogram; it was estimated to be a polyalkylate (U) such as 2,6-diisopropyl-5-methylphenol. The amount of U did not exceed 10%* of all the alkylates.

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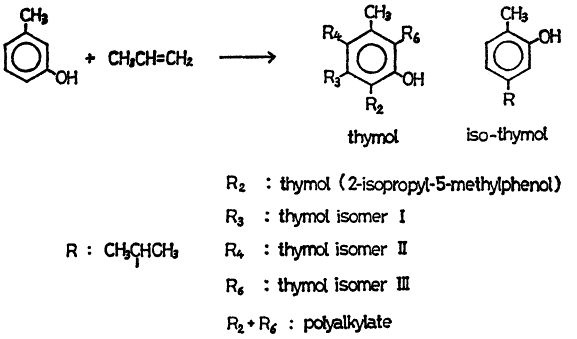
* We assumed the relative mole sensitivity of U to be the same as that (0.78) of thymol isomers to *m*-cresol.



Both the methyl and hydroxyl groups in benzene nuclei are known to have a *para/ortho* orientation effect; most of the products may be, therefore, considered to be *ortho* and *para* isomers with respect to the hydroxyl of *m*-cresol. In the present case, however, the *ortho* alkylates, *i.e.*, thymol and III, were formed in much excess, as will be shown below (Fig. 1).

The catalytic activity changes gradually with the process time, as is shown in Fig. 1. This method of activity change is similar to that observed in the alkylation by zeolite catalysts,[10,11] but not in that by metal sulfate catalysts.[1] This may be due to the existence of an induction period and the catalyst aging.

Surprisingly, in many runs, the selectivity of the γ-Al_2O_3 catalyst for thymol formation had the high value of about 90%, much more than that of the metal sulfate catalyst.[1] In the case of the liquid-phase reaction using a protonic acid catalyst or the Friedel-Crafts catalyst, the thymol selectivity is about 70%.[12]** In addition, those catalysts have the disadvantage of the corrosion of reaction facilities. In this process, the problem does not exist. It can, consequently, be accepted that γ-Al_2O_3 is the most suitable catalyst for the selective formation of thymol.

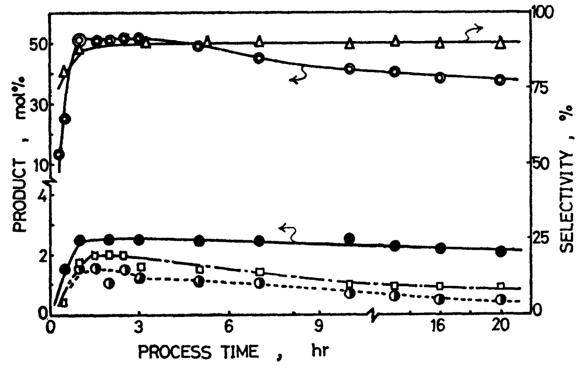


Fig 1. Activity and selectivity changes with process time.
Conditions: W/F=19.5 g·hr/mol, reaction temp=250 °C, propylene/*m*-cresol=1.0 mol/mol. Catalyst: γ-Al_2O_3 calcined at 300 °C. ◎: thymol, ◑: I, □: II, ●: III, △: thymol selectivity.

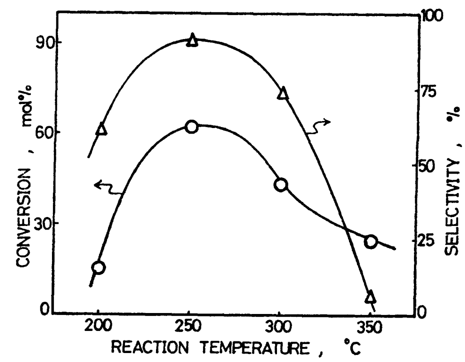


Fig. 2. Effect of reaction temperature on conversion and selectivity.
Conditions: W/F=19.5 g·hr/mol, propylene/*m*-cresol=1.0, calcination temp=400 °C.
○: conversion of *m*-cresol, △: thymol selectivity.

The effects of the reaction conditions on the catalytic activity and selectivity were investigated in detail using the γ-Al_2O_3 calcined at 300 and 400 °C. Furthermore, the active sites and reaction mechanism were discussed.

Effect of the Reaction Temperature. The effect of the reaction temperature on the selectivity of thymol formation was investigated with the γ-Al_2O_3 calcined at 400 °C under a constant contact time (W/F) and a constant mole ratio of reactants. The results are shown in Fig. 2. The optimal reaction temperature was 250 °C. At temperatures higher than 250 °C, the conversion of *m*-cresol decreased with the rise in the temperature. This is attributed to a side reaction, such as the polymerization of the alkylating agent. Further, the selectivity of thymol formation also decreased suddenly because of the formation of many unknowns in addition to U. Many of the unknwons may be alkylates with secondary alkylating agents which are produced by the above side reactions of propylene, or transalkylates. However, the amount of the unknwons was below 10%, as is shown by the single symbol in the right top of Fig. 3.

Figure 3 shows the relation between the reaction temperature and the product distribution. The increase in *iso*-thymol at higher temperatures indicates the occurrence of isomerization or disproportionation.

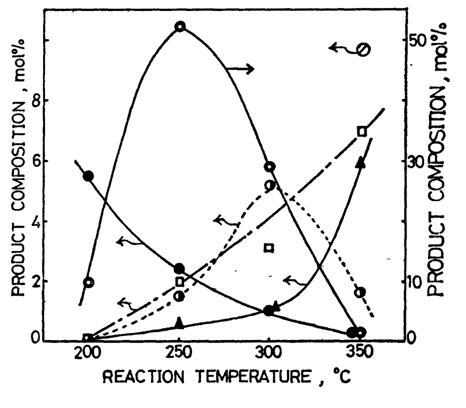


Fig. 3. Relation between reaction temperature and product composition.
Conditions are the same as in Fig. 2.
▲: *iso*-thymol, other symbols are defined in Fig. 1.

** Kolka *et al.* have obtained *o*-alkylphenol selectively in the presence of aluminum phenoxide-type catalyst in liquid phase.[13] For example, in the reaction of phenol and ethylene, 2-ethylphenol and 2,6-diethylphenol selectivities were 68% and 29% respectively (using the same selectivity as we defined here).

Thymol isomer III seems to be unstable energetically and transforms into other thymol isomers at higher temperatures.

Effect of the Contact Time. As an indication of contact time, we used W/F, defined as follows:

$$W/F = \frac{\text{catalyst weight (g)}}{\text{feed rate of reactants (mol/hr)}}$$

The effect of W/F on the convresion of *m*-cresol and on the thymol formation are presented in Fig. 4. The largest conversion was obtained at $W/F \approx 40$. Above this W/F value, there was no noticeable change in the conversion or in the selectivity. The thymol selectivity was constant; it was maintained at a high value of 90% except at low contact times.

At low contact times, thymol and III were formed predominantly and the formation of I and II was very small. With higher contact times, however, the formation of III decreased, while those of thymol, I and II increased. Finally, at $W/F > 20$ the yield of thymol became almost constant. The isomerization of thymol (cyclohexane solution) was carried out using a nitrogen carrier instead of propylene under the same conditions as the alkylation. The resulting products were *m*-cresol, isopropylphenol, I and II, and the unknowns including U. It is, consequently, almost certain that the isomerization and the disproportionation of thymol and III take place during the reaction. It was difficult to estimate the equilibrium composition of thymol isomers in the present experiment because of the unknowns produced.

Effect of Mole Ratio of Reactants. The conversion of *m*-cresol increased with the increase in propylene in the reactant mixture, as is shown in Fig. 5. The thymol selectivity did not change with the mole ratio of propylene to *m*-cresol, whereas *iso*-thymol and U increased. From the standpoint of selective thymol formation, the optimal mole ratio is 1.0.

From these results, the reaction conditions were so chosen that the conversion was large and the thymol selectivity was the highest. The optimal conditions are as follows:

$W/F = 19.5$ (g·hr/mol)

Reaction temperature = 250 °C

Propylene/*m*-cresol = 1.0 (mol/mol)

Further investigations of the active sites of the catalyst have been made under the above conditions.

Catalyst Activation. In general, the activity of solid oxide catalysts changes appreciably with the conditions for activating the catalyst—for example, the calcination temperature and the calcination atmosphere. Therefore, the activity and selectivity of γ-Al_2O_3 have been investigated over a wide range of calcination temperatures between 250 and 900 °C. The results are shown in Fig. 6. Thymol was produced selectively on every catalyst calcined between 250—900 °C. No anomalous product distribution was observed over 250—900 °C, but the activity changed appreciably. For the catalyst calcined at 250 °C, the low activity may be due to the incomplete desorption of materials, such as CO_2 and H_2O, which covered the active sites on the catalyst surface. The results of the physical-property measurements for the catalyst calcined at 900 °C re-

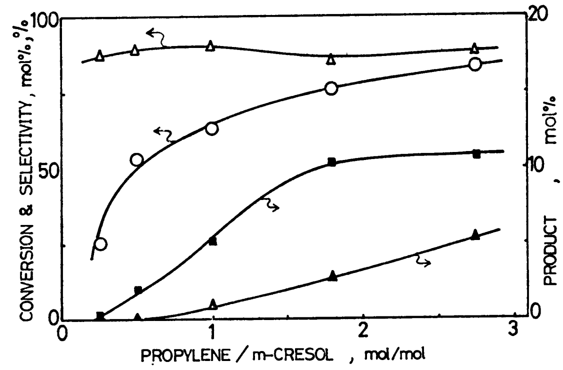


Fig. 5. Effect of mole ratio of reactants (propylene/*m*-cresol).
Conditions: $W/F = 19.5$ g·hr/mol, reaction temp = 250 °C, calcination temp = 300 °C. ▲: *iso*-thymol, ■: unknown (polyalkylate). Other symbols are defined in Fig. 2.

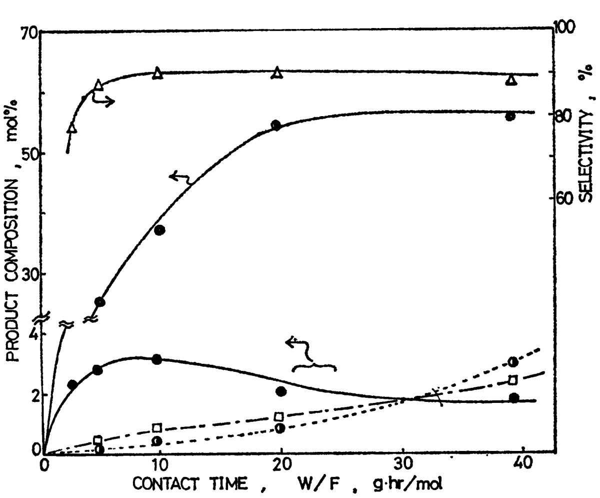


Fig. 4. Effect of change of contact time.
Conditions: reaction temp = 250 °C, propylene/*m*-cresol = 1.0, calcination temp = 300 °C.
Symbols are defined in Figs. 1 and 2.

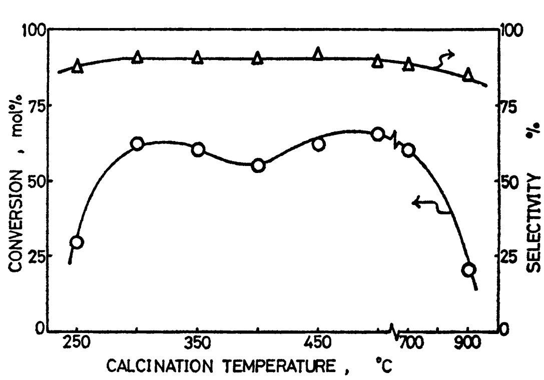


Fig. 6. Activity and selectivity of γ-Al_2O_3 catalyst calcined at various temperatures.
Conditions: calcination atmosphere = $N_2 \leq 500$ °C, air > 500 °C, reaction temp = 250 °C, propylene/*m*-cresol = 1.0, $W/F = 19.5$ g·hr/mol.
Symbols are defined in Fig. 2.

Table 1. Influence of calcination atmosphere of γ-Al_2O_3

Atmosphere[a)]	Conversion[b)] (mol%)	Selectivity (%)
Air	47	89
N_2	63	90
H_2	56	90
O_2	0.4	75

a) Calcination temp=300 °C; 3 hr b) Conditions: W/F=19.5 g·hr/mol, temp=250 °C, propylene/*m*-cresol=1.0.

vealed that the crystal form of alumina changed from the γ to the θ type and that the surface area decreased from 154 to 84 m^2/g. These facts suggest that the differences in the surface structure among aluminas of different calcination temperatures may sensitively result in the differences in the nature of active sites. Such an effect of the calcination temperature on the surface properties of alumina has also been found in studies of the acidity.[5,14)] Therefore, the activity changes with the calcination temperatures may be related to the acidity of the catalyst.

The influence of the calcination atmosphere was next examined. The results are summarized in Table 1. It was found that the catalytic activity of γ-Al_2O_3 varied with the change in the calcination atmosphere. In particular, the activity almost completely disappeared on calcining at 300 °C in an oxygen stream. The activity decrease due to the calcination in the air can apparently be explained by the influence of oxygen in the air. However, the comparison of the X-ray diffraction patterns and the surface area gave little information about the differences in the crystal form of the catalyst calcined in N_2, O_2, H_2, and air. When the catalyst was recalcined at 250 °C for 1 hr in a nitrogen stream after having been calcined at 300 °C for 3 hr in an oxygen stream, the catalytic activity and selectivity were restored to the standard level of N_2 calcination. It may, therefore, be considered that, on the sample calcined in oxygen, the adsorbed oxygen molecules would cover the active sites for alkylation.

Effect of Acid and Base Addition. It has been shown that, in addition to acid sites, basic sites exist on the surface of alumina.[15)] By masking either acidic sites or basic sites it is possible to discern which sites are effective in the isopropylation of *m*-cresol. Before the reaction various acid and base reagents were added to the catalyst in the reaction system at 250 °C and their effects were examined. The results are shown in Table 2. Neither the activity nor the selectivity was changed by the addition of acidic reagents. On the other hand, basic reagents poisoned the catalyst. With the increase in the strength (pK_a value) of the added base the activity fell. Aniline, which is a weaker base, has little effect on the activity. This implies that a weak poison adsorbs reversibly on alumina; that is, the reactant molecules replace the preadsorbed poison molecules. On the contrary, the catalyst was completely deactivated by the addition of stronger bases, such as benzylamine and *n*-butylamine. The alkylation activity decreased with the increase in the amount of the base added, and the depressed activity was restored little with the process time. Therefore, the strong bases are considered to be irreversible poisons. The catalyst partially poisoned with a strong base produced only *ortho* alkylates, *i. e.*, thymol and III (60 mol% and 40 mol% respectively), though the conversion was low. Consequently, it may be concluded that the active sites promoting the isopropylation of *m*-cresol are mainly the acid sites on the γ-Al_2O_3 catalyst.

Catalyst Acidity. It is possible to confirm the existence of the Lewis-type acid sites on γ-Al_2O_3 by means of the coloration of *p*-phenylenediamine. The observed dark violet coloration of this reagent on the alumina indicates the presence of electron-acceptor sites (Lewis-acid sites in the most general sense), because its color is based on the cation radical formed from the reagent.[9)] It is supposed that γ-Al_2O_3 also has weak Brönsted-type acid sites.[3)] From the above results, a correlation can be expected to be seen between the activity and the acidity of each catalyst. We then tried to determine the total amount of the surface acid sites using the method of amine titration

Table 2. Effect of the addition of acidic and basic reagents

Reagent	Amount of addition (mmol)	pK_a	Conversion[a)] (mol%)	Selectivity (%)	Product composition[b)] (mol%) of thymol			
					Thymol	III	I	II
None	—	—	63	90	52	2.2	1.5	2.0
HCl (36%)	10	—	59	89	48	2.2	1.5	1.6
CH_3COOH	10	4.7	55	90	46	2.8	0.8	1.2
CO_2	10	—	57	89	47	2.9	1.1	1.4
H_2O	10	15.5	59	89	48	2.5	1.5	1.8
Aniline	10	4.6[c)]	55	90	49	1.6	0.5	1.0
N,*N*-Diethylaniline	1	6.5[c)]	42	92	37	1.7	0.3	0.8
N,*N*-Diethylaniline	10	6.5[c)]	12	78	9.3	2.3	0	0.2
Benzylamine	1	9.4[c)]	0.5	60	0.3	0.2	0	0
n-Butylamine	1	10.6[c)]	0.4	60	0.2	0.2^-	0	0

a) Conditions: Temp=250 °C, W/F=19.5 g·hr/mol, propylene/*m*-cresol=1.0. b) Other products are *iso*-thymol (~1%) and an unknown(~5%). c) pK_a of the conjugated acid form.

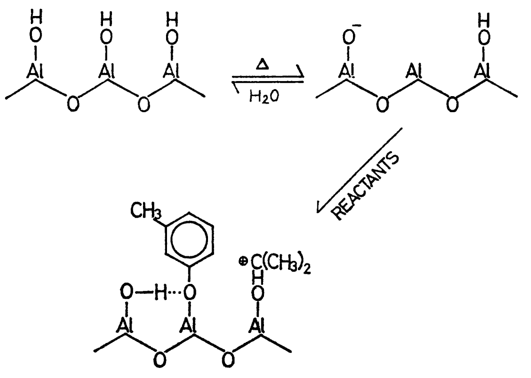
with the Hammett indicators. However, it was very difficult to determine accurately the acidity by this method, because the catalysts were very sensitive to moisture in cooling after the calcination and in the weighing of the sample. It was, therefore, impossible to find a direct correlation between the acidity and the activity.

General Discussion

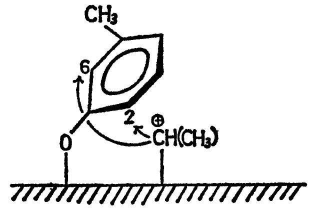
The experimental results showed that the γ-Al_2O_3 catalyst used in the present work has a considerably high selectivity for thymol formation. This seems to suggest that there are some merits of the orientation effect of reactants on the γ-Al_2O_3 surface, at least under the present experimental conditions. Thus, the model for the surface sites on alumina and that for the adsorbed state of *m*-cresol, both proposed by Medema,[5] Peri,[2,3] and Taylor,[8] can favorably be used to discuss the active sites and the reaction mechanism in the present work.

Small numbers of aluminum ions exposed to the surface as a result of the condensation of surface hydroxyl groups form L acid sites on the calcined γ-Al_2O_3. In addition, small numbers of hydroxyl ions of several types persist on the alumina surface even after the calcination at high temperatures; they form B acid sites. Taylor *et al.* showed that phenols form a strongly chemisorbed aluminum phenoxide on γ-Al_2O_3 at 300 °C. They concluded that the cresol molecule is oriented with its aromatic ring almost coplanar with the surface, but is tilted upward so that the *para* position is further from the surface than the *ortho* position. On the other hand, Cvetanovic *et al.*[16] have shown that there are two different sites on the alumina surface for the chemisorption of olefin. They considered that this is an intrinsic property of alumina catalysts. Further, they have suggested that one of the two types of adsorption sites may be Brönsted-type acid centers, and that olefin molecules adsorbed on the sites of this type could transform so as to have the character of chemisorbed carbonium ions.

Based on the above-mentioned surface models proposed by the previous workers and the results of the present work, the alkylation of *m*-cresol with propylene over γ-Al_2O_3 can be pictured as follows:



That is, if *m*-cresol is adsorbed on the L acid sites and if propylene is adsorbed on the neighboring B acid sites, most of the isopropylcarbonium ions will subsequently attack the *ortho* positions (2 and 6 in the following picture) of the adsorbed *m*-cresol, because these positions are closer to the surface.



However, the attack on the 6-position must be subjected to steric hindrance by the methyl group of the adsorbed *m*-cresol. Consequently, propylene may add preferably to the 2-position, and thymol is formed selectively. Kolka also explained the high selectivity of the liquid-phase *ortho* alkylation in terms of the intermediate formation of aluminum phenoxide.[13]

The poisoning action of a strong base appears to be closely related to the irreversible adsorption on active sites. The bonding of the base with aluminum or hydroxyl is much stronger because the nitrogen atom in the base molecule is more basic than the oxygen atom in the *m*-cresol molecule or the double bond in the propylene molecule.

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