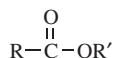


ESTERIFICATION

1. Introduction

This article describes methods for the production of carboxylic esters:



For the properties of these compounds, see ESTERS, ORGANIC. For esters of inorganic acids, see the articles on nitric acid, phosphoric acids, sulfuric acid, etc.

Esters are most commonly prepared by the reaction of a carboxylic acid and an alcohol with the elimination of water. Esters are also formed by a number of other reactions utilizing acid anhydrides, acid chlorides, amides, nitriles, unsaturated hydrocarbons, ethers, aldehydes, ketones, alcohols, and esters (via ester interchange). Detailed reviews of esterification are given in References (1–9).

On the basis of bulk production (10), poly(ethylene terephthalate) manufacture is the most important ester producing process. This polymer is produced by either the direct esterification of terephthalic acid and ethylene glycol, or by the transesterification of dimethyl terephthalate with ethylene glycol. In 1990, poly(ethylene terephthalate) manufacture exceeded 3.47×10^6 t/yr (see POLYESTERS).

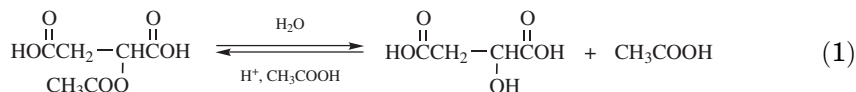
Dimethyl terephthalate is produced by the direct esterification of terephthalic acid and methanol.

Other large-volume esters are vinyl acetate [108-05-4] (VAM, 1.15×10^6 t/yr), methyl methacrylate [80-62-6] (MMA, 0.54×10^6 t/yr), and dioctyl phthalate [117-81-7] (DOP, 0.14×10^6 t/yr). VAM (see VINYL ALCOHOL POLYMERS) is produced for the most part by the vapor-phase oxidative acetoxylation of ethylene. MMA (see METHACRYLIC POLYMERS) and DOP (see PHTHALIC ACIDS) are produced by direct esterification techniques involving methacrylic acid and phthalic anhydride, respectively.

The acetates of most alcohols are also commercially available and have diverse uses. Because of their high solvent power, ethyl, isopropyl, butyl, isobutyl, amyl, and isoamyl acetates are used in cellulose nitrate and other lacquer-type coatings (see CELLULOSE, ESTERS). Butyl and hexyl acetates are excellent solvents for polyurethane coating systems (see COATINGS; URETHANE POLYMERS). Ethyl, isobutyl, amyl, and isoamyl acetates are frequently used as components in flavoring (see FLAVORS AND SPICES), and isopropyl, benzyl, octyl, geranyl, linalyl, and methyl acetates are important additives in perfumes (qv).

2. Reactions Between Organic Acids and Alcohols

In the esterification of organic acids with alcohols, it has been shown that in most cases under acid catalysis, the union is between acyl and alkoxy groups. Acid hydrolysis of acetoxysuccinic acid gives malic acid with retention of configuration at the asymmetric carbon atom (11):



n-Amyl alcohol produced by basic hydrolysis of *n*-amyl acetate with ^{18}O -enriched water does not contain ^{18}O (12).

2.1. Effect of Structure. The rate at which different alcohols and acids are esterified as well as the extent of the equilibrium reaction are dependent on the structure of the molecule and types of functional substituents of the alcohols and acids. Specific data on rates of reaction, mechanisms, and extent of reaction are discussed in the following. More details concerning structural effects are given in References 6, (13–15).

In making acetate esters, the primary alcohols are esterified most rapidly and completely, ie, methanol gives the highest yield and the most rapid reaction. Ethyl, *n*-propyl, and *n*-butyl alcohols react with about equal velocities and conversions. Under the same conditions, the secondary alcohols react much more slowly and afford lower conversions to ester products; however, wide variations are observed among the different members of this series. The tertiary alcohols react slowly, and the conversions are generally low (1–10% conversion at equilibrium). With isobutyl alcohol at 155°C, acids containing a straight-chain (acetic, propionic, and butyric) and phenylacetic and β -phenylpropionic acids are esteri-

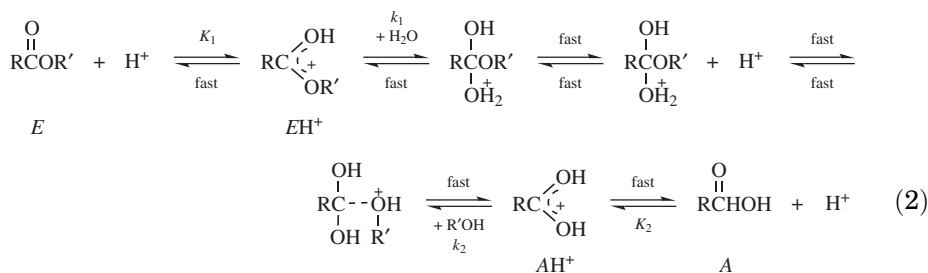
fed readily. Formic acid has the highest initial rate of reaction. The introduction of a branched chain in the acid decreases the rate of esterification, and two branches cause a still greater retarding effect. However, the conversions to ester products from these substituted acids is higher than for the normal straight-chain acids. Similarly, aromatic acids, benzoic and *p*-toluic, react slowly but have high equilibrium conversions.

The introduction of a nitrile group on an aliphatic acid has a pronounced inhibiting effect on the rate of esterification. With the chloroacetic acids, the velocity decreases with increased chlorination. Double bonds also have a retarding influence on the rate of esterification. Tests on substituted acrylic acids have shown that α,β -unsaturated acids are esterified much less easily than the saturated analogues. A triple bond in the α,β position has about the same effect as a double bond. A β,γ -double bond has less of a retarding action. If the double bond is sufficiently removed, as in erucic and brassidic acids (see CARBOXYLIC ACIDS), no effect is noted. Conjugated double bonds, when one is in the α,β -position, afford a great retarding effect. Cis-substituted unsaturated acids esterify more slowly than the trans isomers.

In the preparation of ethyl esters using anhydrous ethyl alcohol and hydrogen chloride catalyst, the rate of esterification of straight-chain fatty acids from propionic through stearic is substantially constant: branching of the fatty acid chain causes retardation. In the saturated dibasic acids, the rate of esterification is a maximum at glutaric acid. The ease of esterification of the cycloparaffin monocarboxylic acids increases in the order C3, C7, C6, C5, and C4 rings; with the exception of cyclopropanecarboxylic acid, these are esterified more rapidly than the corresponding open-chain acids.

Substitutions that displace electrons toward the carboxyl group of aromatic acids diminish the rate of the reaction (16). The substitution of fluoromethoxy or ethoxy groups in the ortho position has an accelerating action, whereas iodo, bromo, nitro, or methyl groups produce retardation. The influence of groups in the meta and para positions is not nearly so marked (17).

2.2. Kinetic Considerations. Extensive kinetic and mechanistic studies have been made on the esterification of carboxylic acids since Berthelot and Saint-Gilles first studied the esterification of acetic acid (18). Although ester hydrolysis is catalyzed by both hydrogen and hydroxide ions (19,20), a base-catalyzed esterification is not known. A number of mechanisms for acid- and base-catalyzed esterification have been proposed (4). One possible mechanism for the bimolecular acid-catalyzed ester hydrolysis and esterification is shown in equation 2 (6).



This mechanism leads to the rate equation (eq. 3) for hydrolysis and to an analogous expression for the esterification (13):

$$-\frac{d[E]}{dt} = \frac{k_1 K_1 [E][H_2O][H^+]}{1 + \alpha} - \frac{k_2 K_2 [A][R'OH][H^+]}{1 + 1/\alpha} \quad (3)$$

In this expression, α depends on those rate coefficients in the above mechanism whose values are assumed to be high. Other mechanisms for the acid hydrolysis and esterification differ mainly with respect to the number of participating water molecules and possible intermediates (21–23).

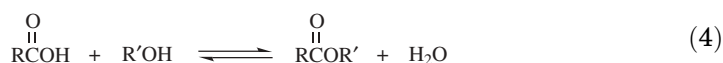
Applications of kinetic principles to industrial reactions are often useful. Initial kinetic studies of the esterification reaction are usually conducted on a small scale in a well stirred batch reactor (24). In many cases, results from batch studies can be used in the evaluation of the esterification reaction in a continuous operating configuration. Generally, the rate of esterification with acid catalyst is proportional to the acid or hydrogen ion concentration as well as the concentration of the alcohols and organic acid. The effect of temperature on the reaction rate is given by the well known Arrhenius equation. These factors are interrelated, and may be used to predict optimum operational conditions for the production of a given ester if the necessary data are available, ie, the order of the reaction under the conditions to be used, a mathematical relation describing the yield with time, and an empirical equation relating the reaction rate constant with temperature, catalyst concentration, and proportions of reactants.

With these kinetic data and a knowledge of the reactor configuration, the development of a computer simulation model of the esterification reaction is invaluable for optimizing esterification reaction operation (25–28). However, all esterification reactions do not necessarily permit straightforward mathematical treatment. In a study of the esterification of 2,3-butanediol and acetic acid using sulfuric acid catalyst, it was found that the reaction occurs through two pairs of consecutive reversible reactions of approximately equal speeds. These reactions do not conform to any simple first-, second-, or third-order equation, even in the early stages (29).

In a study of the kinetics of the reaction of 1-butanol with acetic acid at 0–120°C, an empirical equation was developed that permits estimation of the value of the rate constant with a deviation of 15.3% from the molar ratio of reactants, catalyst concentration, and temperature (30). This study was conducted using sulfuric acid as catalyst with a mole ratio of 1-butanol to acetic acid of 3:19.6, and a catalyst concentration of 0–0.14 wt%.

Similar studies have been performed on the formation of mono *n*-butyl phthalate at 80–150°C with sulfuric acid catalyst (31). The reaction of phthalic anhydride with mono *n*-butyl phthalate to afford di *n*-butyl phthalate is complete in 10 min at 100°C with 1 wt% catalyst.

2.3. Equilibrium Constants. The reaction between an organic acid and an alcohol to produce an ester and water is expressed in equation 4:



This was first demonstrated in 1862 by Berthelot and Saint-Gilles (32), who found that when equivalent quantities of ethyl alcohol and acetic acid were allowed to react, the esterification stopped when two-thirds of the acid had reacted. Similarly, when equal molar proportions of ethyl acetate and water were heated together, hydrolysis of the ester stopped when about one-third of the ester was hydrolyzed. By varying the molar ratios of alcohol to acid, yields of ester >66% were obtained by displacement of the equilibrium. The results of these tests were in accordance with the mass action law shown in equation 5.

$$K = [\text{ester}][\text{water}]/[\text{acid}][\text{alcohol}] \quad (5)$$

However, in many cases the equilibrium constant is affected by the proportion of reactants (7,33,34). The temperature as well as the presence of salts may also affect the value of the equilibrium constant (35,36).

The effect of water on the equilibrium constant for the reaction of 1 mol of ethanol, 1 mol of acetic acid, and 23 moles of water has been investigated. This mixture has an equilibrium constant of 3.56, compared with 3.79 for the reaction with anhydrous materials (7,37).

Theoretical yields of ester obtainable with proportions of reactants are shown in Figure 1 for four values of the equilibrium constant. Thus when K equals 10 (esters of *p*-toluic acid with primary alcohols), with equivalent amounts of acid and alcohol, a yield of about 76% may be expected.

In general, esters having equilibrium constants below unity are not prepared by direct interaction of alcohol and acid; in these cases, the acid anhydrides or acid chlorides are used, since the equilibrium favors the ester product.

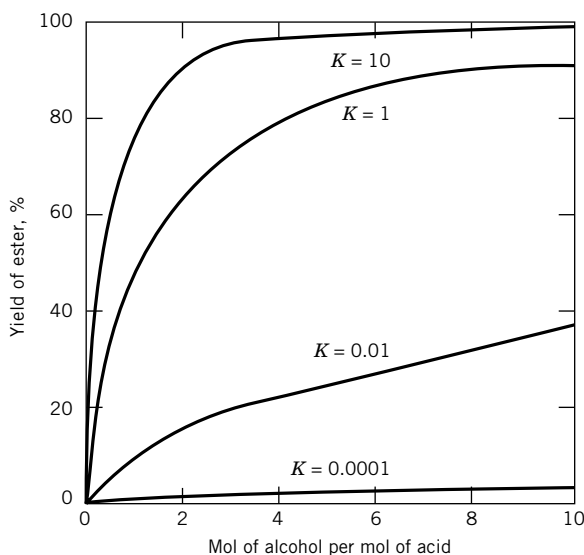


Fig. 1. Theoretical yields of ester obtainable with varying proportions of reactants for different values of equilibrium constant.

2.4. Completion of Esterification. Because the esterification of an alcohol and an organic acid involves a reversible equilibrium, these reactions usually do not go to completion. Conversions approaching 100% can often be achieved by removing one of the products formed, either the ester or the water, provided the esterification reaction is equilibrium limited and not rate limited. A variety of distillation methods can be applied to afford ester and water product removal from the esterification reaction (see DISTILLATION). Other methods such as reactive extraction and reverse osmosis can be used to remove the esterification products to maximize the reaction conversion (38). In general, esterifications are divided into three broad classes, depending on the volatility of the esters:

1. Esters of high volatility, such as methyl formate, methyl acetate, and ethyl formate, have lower boiling points than those of the corresponding alcohols, and therefore can be readily removed from the reaction mixture by distillation.
2. Esters of medium volatility are capable of removing the water formed by distillation. Examples are propyl, butyl, and amyl formates, ethyl, propyl, butyl, and amyl acetates, and the methyl and ethyl esters of propionic, butyric, and valeric acids. In some cases, ternary azeotropic mixtures of alcohol, ester, and water are formed. This group is capable of further subdivision: with ethyl acetate, all of the ester is removed as a vapor mixture with alcohol and part of the water, while the balance of the water accumulates in the system. With butyl acetate, on the other hand, all of the water formed is removed overhead with part of the ester and alcohol, and the balance of the ester accumulates as a high boiler in the system.
3. Esters of low volatility are accessible via several types of esterification. In the case of esters of butyl and amyl alcohols, water is removed as a binary azeotropic mixture with the alcohol. To produce esters of the lower alcohols (methyl, ethyl, propyl), it may be necessary to add a hydrocarbon such as benzene or toluene to increase the amount of distilled water. With high boiling alcohols, ie, benzyl, furfuryl, and β -phenylethyl, an accessory azeotroping liquid is useful to eliminate the water by distillation.

Use of Azeotropes to Remove Water. With the aliphatic alcohols and esters of medium volatility, a variety of azeotropes is encountered on distillation (see DISTILLATION, AZEOTROPIC AND EXTRACTIVE). Removal of these azeotropes from the esterification reaction mixture drives the equilibrium in favor of the ester product (39).

Binary azeotropes may be formed between the alcohol and water, the alcohol and ester, and the ester and water. Ternary azeotropes involving the alcohol, ester, and water are also possible. In general, the ternary azeotropes have the lowest boiling points, but the differences between the boiling points of the various combinations in some instances are very small. The ester–water binaries have boiling points close to those of the ternary mixtures. An extremely efficient fractionating column is usually required to obtain a pure ternary azeotrope. Binary azeotropes of the alcohol and water may be utilized in the preparation

of the higher boiling, nonvolatile esters for completion of the reaction (39). Almost all of the alcohols (up to C₂₀-alcohols) except methanol form binary azeotropes with water. The azeotropes formed by water with ethyl, *n*-propyl, isopropyl, allyl, and *tert*-butyl alcohols are single phase, ie, on condensation of the vapor, the components are completely miscible. Other means to eliminate water are often necessary: extraction of the ester with a water-insoluble solvent, eg, benzene, cyclohexane, or carbon tetrachloride; reactive distillation; drying with potassium carbonate; or salting out. The higher alcohols form azeotropes that on condensation separate into two liquid phases; in such a case, the alcohol-rich phase can be separated by further distillation into azeotrope and pure alcohol, and the water-rich phase into azeotrope and water. Under certain conditions, entraining gases are used to facilitate the removal of water (40).

Use of Desiccants and Chemical Means to Remove Water. Another means to remove the water of esterification is calcium carbide supported in a thimble of a continuous extractor through which the condensed vapor from the esterification mixture is percolated (41) (see CARBIDES). A column of activated bauxite (Florite) mounted over the reaction vessel has been used to remove the water of reaction from the vapor by adsorption (42).

2.5. Catalysts. The choice of the proper catalyst for an esterification reaction is dependent on several factors (43–46). The most common catalysts used are strong mineral acids such as sulfuric and hydrochloric acids. Lewis acids such as boron trifluoride, tin and zinc salts, aluminum halides, and organo-titanates have been used. Cation-exchange resins and zeolites are often employed also.

In laboratory preparations, sulfuric acid and hydrochloric acid have classically been used as esterification catalysts. However, formation of alkyl chlorides or dehydration, isomerization, or polymerization side reactions may result. Sulfonic acids, such as benzenesulfonic acid, *p*-toluenesulfonic acid, or methanesulfonic acid, are widely used in plant operations because of their less corrosive nature. Phosphoric acid is sometimes employed, but it leads to rather slow reactions. Soluble or supported metal salts minimize side reactions but usually require higher temperatures than strong acids.

Acid-Regenerated Cation Exchangers. The use of acid-regenerated cation resin exchangers (see ION EXCHANGE) as catalysts for effecting esterification offers distinct advantages over conventional methods. Several types of cation-exchange resins can be used as solid catalysts for esterification (47,48). In general, the strongly acidic sulfonated resins comprised of copolymers of styrene, ethylvinylbenzene, and divinylbenzene are used most widely. With the continued improvement of ion-exchange resins, such as the macroporous sulfonated resins, esterification has become one of the most fertile areas for use of these solid catalysts. With low molecular weight acids and alcohols, in most cases the resin structure has minimal effect on the yield or kinetics of the esterification as long as the catalyst contains strongly acidic groups. The kinetics in batch and tubular reactors of the esterification of 1-butanol with acetic acid catalyzed by a macroporous sulfonated polystyrene exchange resin have been studied. The catalytic activity was dependent on the water content of the resin and the rate determining step is the surface reaction of the chemisorbed acid and adsorbed alcohol (49).

Table 1. Tests Using Amberlite IR-120 to Esterify Diethylene Glycol (DEG)

Acid	DEG, mol/mol acid	IR-120, g/100 g acid	Temp, °C	Reaction time, h	Monoester, % conv	Diester, % conv
lauric	1	7.5	140	18	24	71
lauric	4	15.5	130	10	71	21
lauric	6	7.5	140	18	86	11
lauric	12	15.0	132	18	100	
oleic	12	10.6	140	18	100	
stearic	12	8.9	150	18	100	
benzoic	2	24.6	140	4	75	

Despite the higher cost compared with ordinary catalysts, such as sulfuric or hydrochloric acid, the cation exchangers present several features that make their use economical. The ability to use these agents in a fixed-bed reactor operation makes them attractive for a continuous process (50,51). Cation-exchange catalysts can be used also in continuous stirred tank reactor (CSTR) operation.

The resin (Amberlite IR-116 and Amberlite IR-120B) catalyzed continuous esterification of butanol or 2-ethylhexanol with acrylic acid is a novel example. High conversion and selectivity to the acrylate ester are accomplished. The CSTR in this application has advantage over a fixed-bed configuration since water separation from the higher boiling ester product in the reactor is more rapid, and this leads to a higher conversion with fewer by-products. The type of exchange resin also affects the esterification. The degree of cross-linking, porosity, and surface area of the strongly acid cation-exchange resin in combination with the back-mixed reactor design are critical factors to minimize secondary by-product formation and polymeric fouling of the resin catalyst (46).

The esterification of *n*-butyl alcohol and oleic acid with a phenol-formaldehydesulfonic acid resin (similar to amberlite IR-100) is essentially second order after an initial slow period (52). The velocity constant is directly proportional to the surface area of the catalyst per unit weight of reactants.

A series of tests using Amberlite IR-12 (sulfonated polystyrene resin) to esterify diethylene glycol (DEG) using toluene as the entrainer for removal of water gave the results in Table 1 (53).

Recovery of dilute acetic acid is achieved by esterification with methanol using a sulfonated resin (Dowex 50w) in a packed distillation column (54). Pure methyl acetate is obtained. This reaction is second order in acetic acid, zero order in methanol, and partially diffusion controlled.

3. Batch Esterification

3.1. Ethyl Acetate. A typical plant configuration for production of ethyl acetate [141-78-6] as a low boiling overhead product relative to water is shown in Figure 2 (2). The esterification reactor is a cylindrical tank, or still pot, heated by a closed-coil steam pipe. The reactor is charged with acetic acid, 95% ethanol, and concentrated sulfuric acid. The temperature at the top of the fractionating

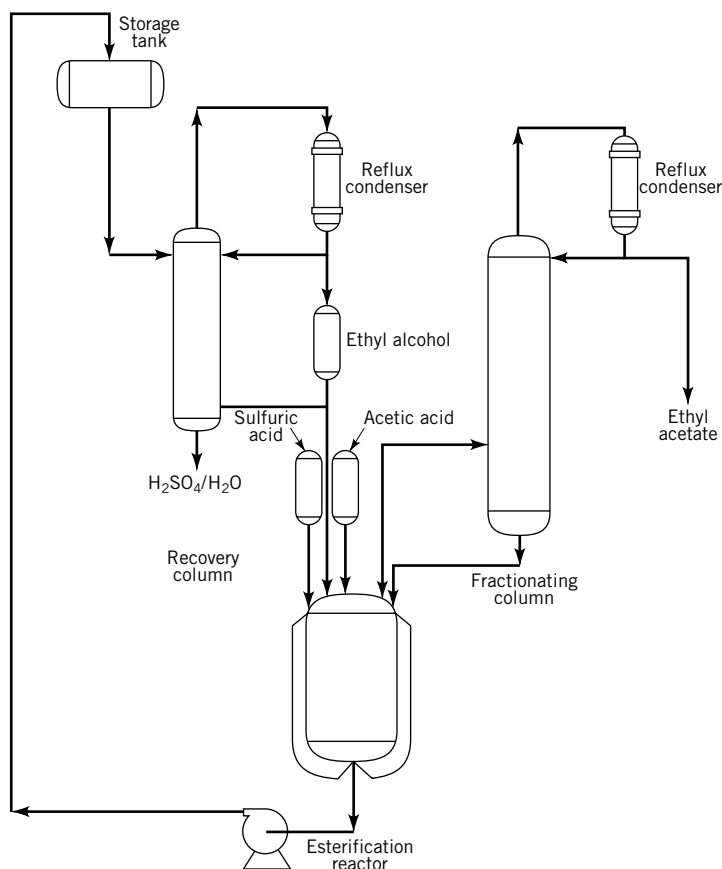


Fig. 2. Batch ethyl acetate process (2).

column is maintained at ca 70°C to give a ternary azeotropic mixture of ca 83% ethyl acetate, 9% alcohol, and 8% water. The vapor is condensed, part of it is returned to the top plate of the column as reflux, and the remainder is drawn off to storage. The ternary azeotrope (production-grade ethyl acetate) is satisfactory for many commercial purposes, but for an alcohol-free and water-free ester, further purification is needed.

3.2. *n*-Butyl Acetate. Equipment used for the batch esterification to give butyl acetate [123-86-4] is shown in Figure 3. Glacial acetic acid is mixed with an excess of butyl alcohol and a small amount of concentrated sulfuric acid in the esterification reactor. The mixture is heated for several hours by means of a steam jacket to give esterification equilibrium. After the preliminary heating, slow rectification is permitted to remove the water already formed and thus increase the yield. The esterification is continued until no more water separates. At this point, the temperature at the top of the column rises, and the percentage of acetic acid in the distillate increases. It is necessary to neutralize the small amount of acid remaining in the esterification reactor before further distillation. A solution of sodium hydroxide is added to the esterification reactor,

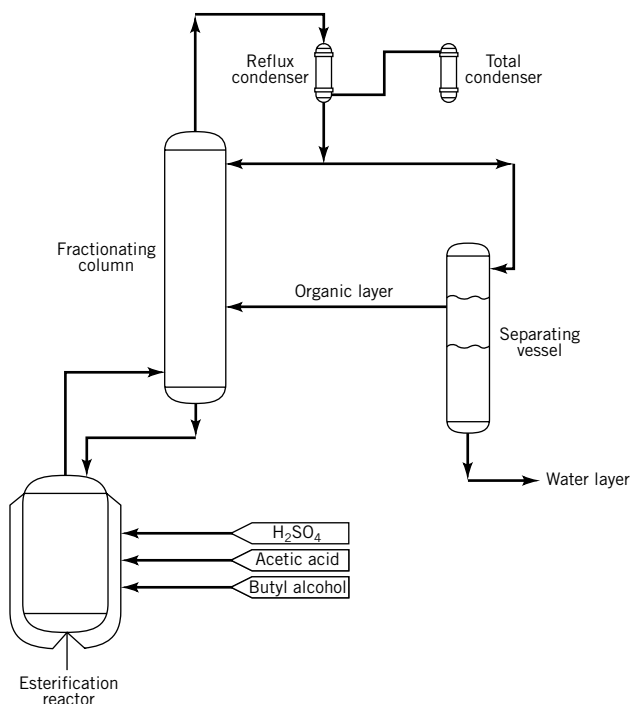


Fig. 3. Batch *n*-butyl acetate process (2).

and the mixture is allowed to stand to form a water layer that is removed. The organic ester layer (upper layer) is then washed with water and distilled to obtain an overhead butyl acetate product of 75–85% purity; the remainder is butyl alcohol.

4. Continuous Esterification

The law of mass action, the laws of kinetics, and the laws of distillation all operate simultaneously in a process of this type. Esterification can occur only when the concentrations of the acid and alcohol are in excess of equilibrium values; otherwise, hydrolysis must occur. The equations governing the rate of the reaction and the variation of the rate constant (as a function of such variables as temperature, catalyst strength, and proportion of reactants) describe the kinetics of the liquid-phase reaction. The usual distillation laws must be modified, since most esterifications are somewhat exothermic and reaction is occurring on each plate. Since these kinetic considerations are superimposed on distillation operations, each plate must be treated separately by successive calculations after the extent of conversion has been determined (see DISTILLATION).

Continuous esterification of acetic acid in an excess of *n*-butyl alcohol with sulfuric acid catalyst using a four-plate single bubblecap column with reboiler has been studied (55). The rate constant and the theoretical extent of reaction

were calculated for each plate, based on plate composition and on the total incoming material to the plate. Good agreement with the analytical data was obtained.

A continuous distillation process has been studied for the production of high boiling esters from intermediate boiling polyhydric alcohols and low boiling monocarboxylic aliphatic or aromatic acids (56). The water of reaction and some of the organic acid were continuously removed from the base of the column.

4.1. Methyl Acetate. High purity methyl acetate [79-20-9] is required for the rhodium catalyzed carbonylation process to produce acetic anhydride (57). In the most recently developed commercial process for the manufacture of high purity methyl acetate, acetic acid functions both as a reactant and as an extractant in a countercurrent reactive distillation column (58,59), thereby alleviating the problem of azeotrope formation. This methyl acetate purification process obviates the use of additional vacuum or extractive distillation means to separate methyl acetate from its low boiling water and methanol azeotropes (60,61). As shown in Figure 4, this process uniquely demonstrates the use of reactive distillation as a means to produce essentially dry methyl acetate. The esterification reaction catalyzed by sulfuric acid occurs in the middle of the column. Acetic acid is fed to the top portion of the reactor section, and the methanol is fed to the lower portion of the reactor section. The countercurrent flow of acetic acid and methyl acetate with its azeotropes is used to remove water and by-products from methyl acetate. Below the acetic acid feed and above the reaction

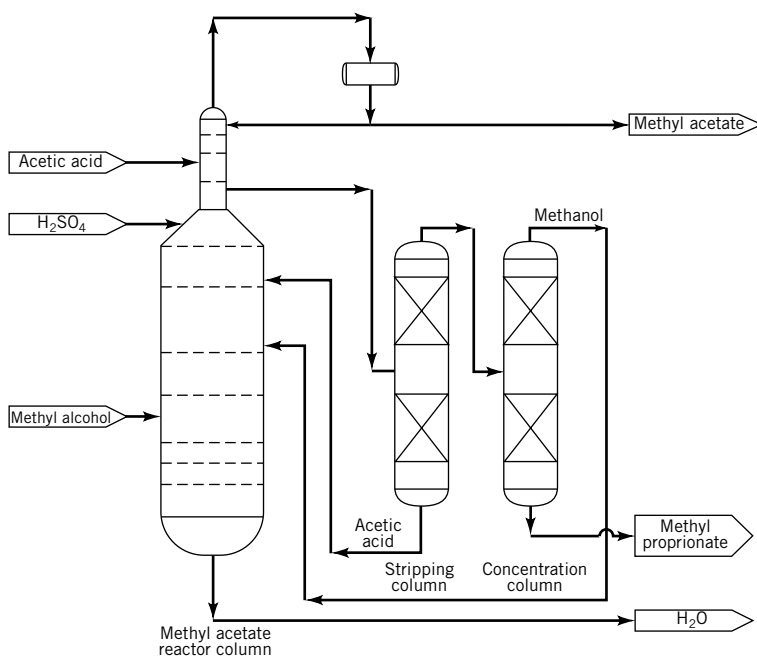


Fig. 4. Continuous methyl acetate process (59).

section, water and some methanol are extracted from methyl acetate using acetic acid. Acetic acid and methyl acetate are then separated above the acetic acid feed in the rectification portion of the column. High purity methyl acetate (at least 99.5 wt% methyl acetate) is isolated from the column overhead. The catalyst and impurities (primarily methyl propionate and isopropyl acetate) are removed from the reactor section by a sidedraw. Methanol in turn is stripped from the water in the lower portion of the column below the methanol feed. The impurities are further concentrated and removed from the process in two distillation columns with catalyst and acetic acid being recycled back to the reactive distillation column.

4.2. Ethyl Acetate. The production of ethyl acetate by continuous esterification is an excellent example of the use of azeotropic principles to obtain a high yield of ester (2). The acetic acid, concentrated sulfuric acid, and an excess of 95% ethyl alcohol are mixed in reaction tanks provided with agitators. After esterification equilibrium is reached in the mixture, it is pumped into a receiving tank and through a preheater into the upper section of a bubblecap plate column (Fig. 5). The temperature at the top of this column is maintained at ca 80°C and its vapor (alcohol with the ester formed and ca 10% water) is passed to a condenser. The first recovery column is operated with a top temperature of 70°C, producing a ternary azeotrope of 83% ester, 9% alcohol, and 8% water. The ternary mixture is fed to a static mixer where water is added in order to form two layers and allowed to separate in a decanter. The upper layer contains ca 93% ethyl acetate, 5% water, and 2% alcohol, and is sent to a second recovery or ester-drying column. The overhead from this column is 95–100% ethyl acetate which is sent to a cooler and then to a storage tank. This process also applies to methyl butyrate.

5. Vapor-Phase Esterification

Catalytic esterification of alcohols and acids in the vapor phase has received attention because the conversions obtained are generally higher than in the corresponding liquid-phase reactions (7).

5.1. Physicochemical Considerations. The determination of the equilibrium constant K_G for the reaction $\text{C}_2\text{H}_5\text{OH} + \text{CH}_3\text{COOH} = \text{C}_2\text{H}_5\text{OOCH}_3 + \text{H}_2\text{O}$ has been the subject of a number of investigations over the temperature range of 40–300°C (62). The values of the equilibrium constant range from 6–559 (63) with 71–95% ester as the equilibrium concentration from an equimolar mixture of ethyl alcohol and acetic acid, depending on the technique used. A study of the reaction mechanism indicates that adsorption of acetic acid is the rate-controlling step; the molecularly adsorbed acetic acid then reacts with alcohol in the vapor phase. The rate of esterification of acetic acid and ethyl alcohol in equimolar quantities has been studied in a dynamic system using silica gel catalyst at 150–270°C (64).

5.2. Ethyl Acetate. Catalysts proposed for the vapor-phase production of ethyl acetate include silica gel, zirconium dioxide, activated charcoal, and potassium hydrogen sulfate. More recently, phosphoric-acid-treated coal (65) and calcium phosphate (66) catalysts have been described.

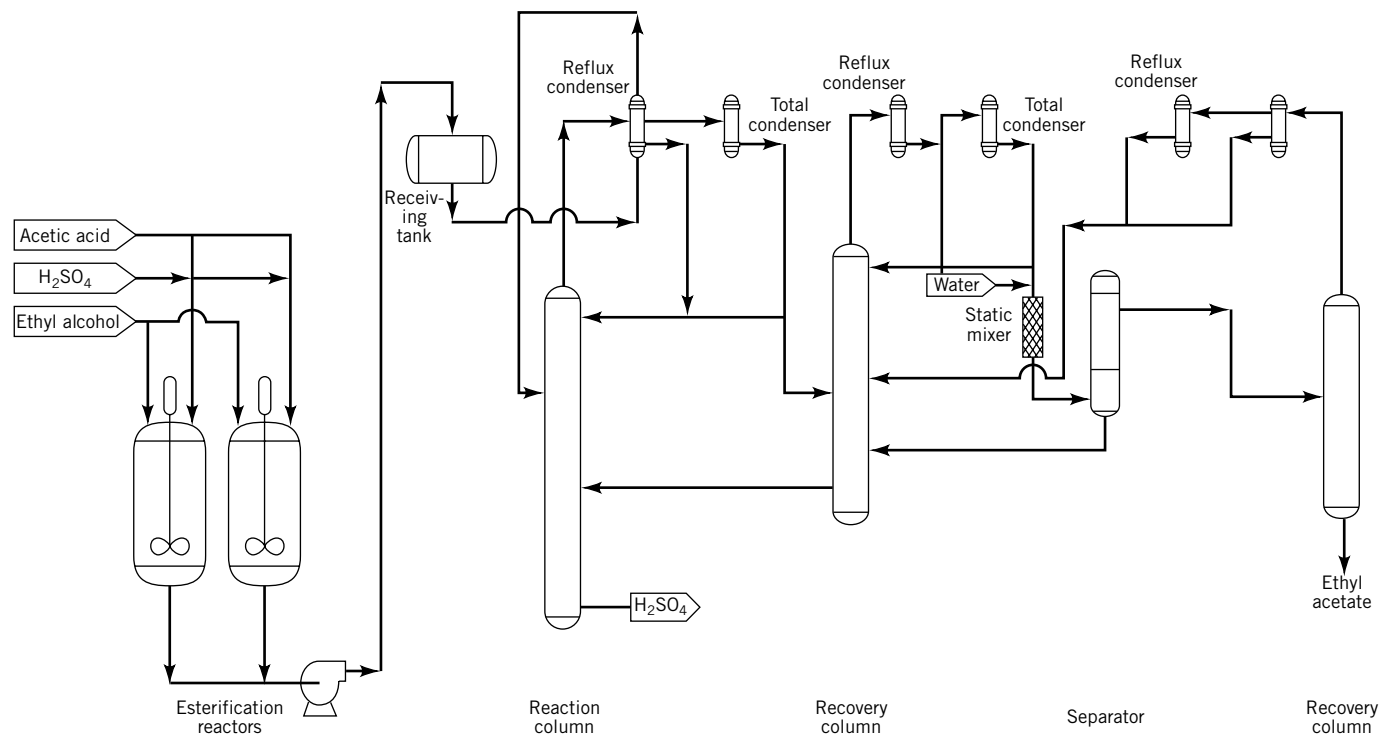
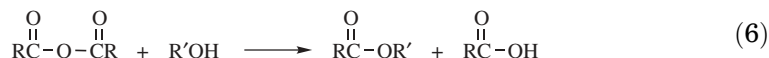


Fig. 5. Continuous ethyl acetate process (2).

5.3. Other Esters. The esterification of acetic acid with various alcohols in the vapor phase has been studied using several catalysts precipitated on pumice (67).

6. Esterification of Other Compounds

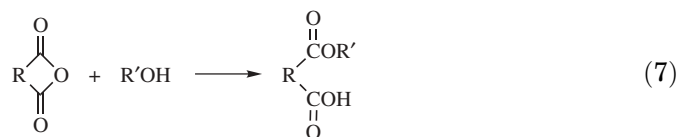
6.1. Acid Anhydrides. Acid anhydrides react with alcohols to form esters (in high yields in many cases) with a carboxylic acid formed as by-product:



However, this method is applied only when esterification cannot be effected by the usual acid-alcohol reaction because of the higher cost of the anhydrides. The production of cellulose acetate (see FIBERS, CELLULOSE ESTERS), phenyl acetate (used in acetaminophen production), and aspirin (acetylsalicylic acid) (see SALICYLIC ACID) are examples of the large-scale use of acetic anhydride. The speed of acylation is greatly increased by the use of catalysts (68) such as sulfuric acid, perchloric acid, trifluoroacetic acid, phosphorus pentoxide, zinc chloride, ferric chloride, sodium acetate, and tertiary amines, eg, 4-dimethylaminopyridine.

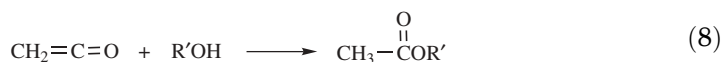
Formic anhydride is not stable. However, formate esters of alcohols and phenolics can be prepared using formic-acetic anhydride (69,70). Anhydrides can also be incorporated into polystyrene backbones which can then be treated with alcohols to afford the corresponding esters and carboxypolystyrene for recycle (71).

Dibasic acid anhydrides such as phthalic anhydride and maleic anhydride readily react with alcohols to form the monoalkyl ester:



This reaction can be used for identification of individual alcohols because of the wide variations noted in the melting points of monoalkyl esters up to the dodecyl derivatives. The reaction can be used to separate alcohols of various classes. Monoesters are converted into the normal diesters by heating with an excess of alcohol and a catalyst; however, diesters are generally formed directly from the corresponding diacids.

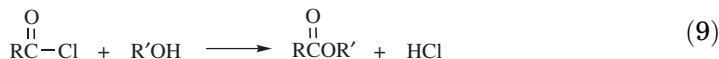
Ketene, like acid anhydrides, reacts with alcohols to form (acetate) esters:



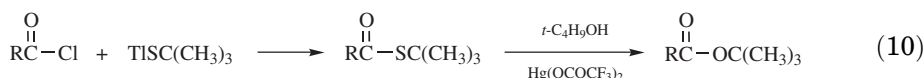
Ketene is an efficient acetylating agent with some alcohols, but in the absence of catalysts may be either nonreactive or sluggish with others, especially phenols and tertiary alcohols (72) (see KETENES AND RELATED SUBSTANCES).

6.2. Acid Chlorides.

Acid chlorides react with alcohols to form esters:



The acid chlorides are generally more reactive than the corresponding acid anhydrides. In fact, the alcoholysis of acid chlorides is probably the best laboratory method for preparing esters. Frequently, basic materials are added during the course of the reaction to neutralize by-product hydrochloric acid. When the basic material is aqueous caustic, the procedure is referred to as the Schotten-Baumann procedure (73). Esterification of tertiary alcohols by acid chlorides is described in Reference 74. Esters of tertiary alcohols can also be formed through an intermediate *t*-butyl thioate group (75):



Acid chlorides are used for the quantitative determination of hydroxyl groups and for acylation of sugars. Industrial applications include the formation of the alkyl or aryl carbonates from phosgene (see CARBONIC AND CHLOROFORMIC ESTERS) and phosphate esters such as triethyl, triphenyl, tricresyl, and tritolyl phosphates from phosphorus oxychloride.

The reaction of alcohols and acid chlorides in the presence of magnesium has been described (68). With primary and secondary alcohols the reaction is very smooth, and affords high and sometimes quantitative yields. Difficulty esterifiable hydroxy compounds such as tertiary alcohols and phenols can be esterified by this method. The reaction carried out in ether or benzene is usually very vigorous with evolution of hydrogen.

6.3. Amides. Alcoholysis of amides provides another method for synthesizing esters:



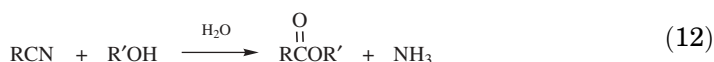
In order to produce high yields of ester in this manner it is necessary to remove the by-product ammonia (or amine) either by heating or combining with mineral acid, eg, H_2SO_4 or HCl . Recent work has shown that acidic ion-exchange resins can be used in place of mineral acids for converting sensitive unsubstituted amides (76). The structural relationships involved in esterification of amides are shown in Table 2 (77).

Other methods of converting amides to esters have been described (78). Alkyl halides can be treated with amides to give esters (79). Also, esters can be synthesized from *N*-alkyl-*N*-nitrosoamides, which are derived from the corresponding amides (80).

6.4. Nitriles. Alcoholysis of nitriles offers a convenient way to produce esters without isolating the acid:

Table 2. Comparative Yields of Esters from Amides or Acids

Methyl ester	Yield of ester, %	
	From amide	From acid
formate	34	
acetate	70	56
monochloroacetate	64	65
dichloroacetate	57	70
trichloroacetate	53	73
phenylacetate	50	86
propionate	80	44
benzoate	15	37



Acids are used to combine with the ammonia formed. A large excess of alcohol is used, but the amount of water is generally kept small. Catalysts such as hydrogen chloride, hydrogen bromide, and sulfuric acid have been employed (71).

One of the most important applications of this process is that of methyl methacrylate manufacture. In this process (81), acetone cyanohydrin is treated with sulfuric acid at 100°C, affording the corresponding methacrylamide sulfate which is esterified with methanol. After purification, methyl methacrylate (99.8% purity) is obtained in a yield of ca 85%.

6.5. Unsaturated Hydrocarbons. Olefins from ethylene through octene have been converted into esters via acid-catalyzed nucleophilic addition. With ethylene and propylene, only a single ester is produced using acetic acid, ethyl acetate and isopropyl acetate, respectively. With the butylenes, two products are possible: *sec*-butyl esters result from 1- and 2-butylenes, whereas *tert*-butyl esters are obtained from isobutylene. The C5 olefins give rise to three *sec*-amyl esters and one *t*-amyl ester. As the carbon chain is lengthened, the reactivity of the olefin with organic acids increases.

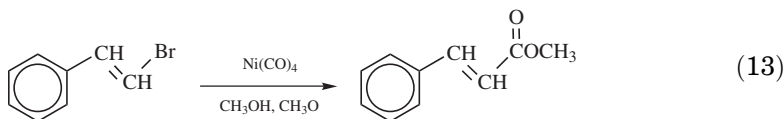
In the case of ethylene, it is necessary to use high temperatures and pressures as well as active catalyst to effect esterification (82). Yields of 40–50% based on ethylene were obtained with boron trifluoride–hydrogen fluoride mixtures as catalysts at 150°C. 2-Butene under pressure at 115–120°C with an excess of glacial acetic acid containing 10% H₂SO₄ gave as much as a 60% yield of *sec*-butyl acetate (83).

tert-Butyl acetate [540-88-5] was prepared by passing isobutylene and acetic acid (2:1 mol ratio) in the liquid phase over a silica catalyst impregnated with vanadium pentoxide and potassium sulfate at 1.7 MPa (250 psi). Conversion of isobutylene to ester increased with increasing temperature and ranged from 10% at 52°C to 24% at 93°C. Based on the acetic acid charged, yields of 31–43% of *t*-butyl acetate resulted at 93°C (84).

Most of the vinyl acetate produced in the United States is made by the vapor-phase ethylene process. In this process, a vapor-phase mixture of ethylene, acetic acid, and oxygen is passed at elevated temperature and pressures over a fixed-bed catalyst consisting of supported palladium (85). Less than 70% oxygen,

acetic acid, and ethylene conversion is realized per pass. Therefore, these components have to be recovered and returned to the reaction zone. The vinyl acetate yield using this process is typically in the 91–95% range (86). Vinyl acetate can be manufactured also from acetylene, acetaldehyde, and the liquid-phase ethylene process (see VINYL POLYMERS).

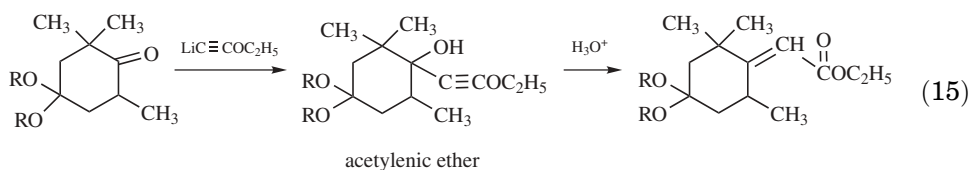
Esters can be obtained from halogenated olefins using a metal carbonyl catalyst (87), eg, *trans*-1-bromo-2-phenylethylene is treated with nickel carbonyl in the presence of methanol to afford the corresponding methyl cinnamate (see CINNAMIC ACID).



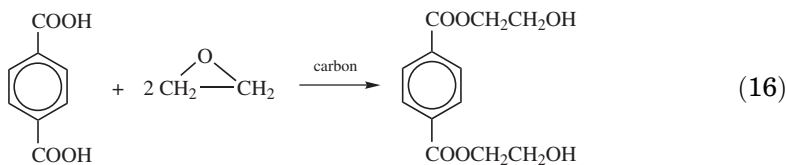
6.6. Ethers. In the presence of anhydrous agents such as ferric chloride (88), hydrogen bromide, and acid chlorides, ethers react to form esters (see ETHERS). Esters can also be prepared from ethers by an oxidative process (89). With mixed sulfonic–carboxylic anhydrides, ethers are converted to a mixture of the corresponding carboxylate and sulfonate esters (90):



Unsaturated esters can be prepared from the corresponding acetylenic ethers with yields in most cases of >50% (91) as in the following example:



β -hydroxyethyl esters can be prepared from carboxylic acids and ethylene oxide:



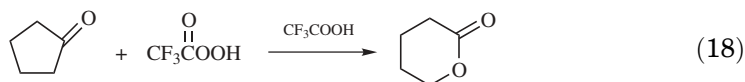
Bis-(β -hydroxyethyl) terephthalate and related compounds can be produced in this manner using finely divided carbon catalyst (92). The carbon functions not only as a catalyst but also helps to remove color from the reaction mixture upon removal of the carbon by hot filtration.

6.7. Aldehydes and Ketones. Esters are obtained readily by condensation of aldehydes in the presence of alcoholate catalysts such as aluminum ethylate, $\text{Al}(\text{OC}_2\text{H}_5)_3$, by the Tishchenko reaction. The alcoholate catalysts may be prepared from commercial aluminum and *n*-butyl or isobutyl alcohol in the presence of 2–5% aluminum chloride (93).

Trihalomethyl ketones react with alcohols in the presence of alkaline catalysts even at room temperature (94):

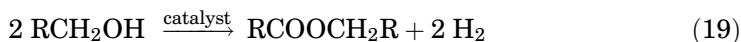


A variety of esters can be prepared from the corresponding ketones using peracids in a process usually referred to as the Baeyer-Villiger reaction (95); ie, cyclopentanone is converted to δ -valerolactone upon treatment of the ketone with peroxytrifluoroacetic acid:



This conversion can be carried out, in many cases, with >80% yield.

6.8. Alcohols. The direct synthesis of esters by dehydrogenation or oxidative hydrogenation of alcohols offers a simple method for the preparation of certain types of esters, such as ethyl acetate (96–98):



The reaction is catalyzed by copper with various promoters or activators, and is carried out in the vapor phase at 200–300°C.

7. Technical Preparation of Esters

Esterification is generally carried out by refluxing the reaction mixture until the carboxylic acid has reacted with the alcohol and the water has been split off. The water or the ester is removed from the equilibrium by distillation. The choice of the esterification process to obtain a maximum yield is dependent on many factors, ie, no single process has universal applicability. Although extensive preparative techniques have been reviewed elsewhere (7,68), the methods given in this section are representative of both laboratory and plant-scale techniques used in batch esterifications.

7.1. Methyl Esters. Methyl esters are obtained in good yield using methylene dichloride or ethylene dichloride as solvent (99). The latter is generally preferred, but the choice of the solvent depends to some extent on the boiling point of the desired ester. Also, the toxicity of these solvents should be considered prior to using them (see CHLOROCARBONS AND CHLOROHYDROCARBONS). The general procedure is as follows: for each mole of aliphatic carboxyl group, 96 g (3 mol) of methanol, 300 mL of ethylene dichloride, and 3 mL of concentrated H_2SO_4 are used. With aromatic acids, the amount of H_2SO_4 is increased to 15 mL/mol

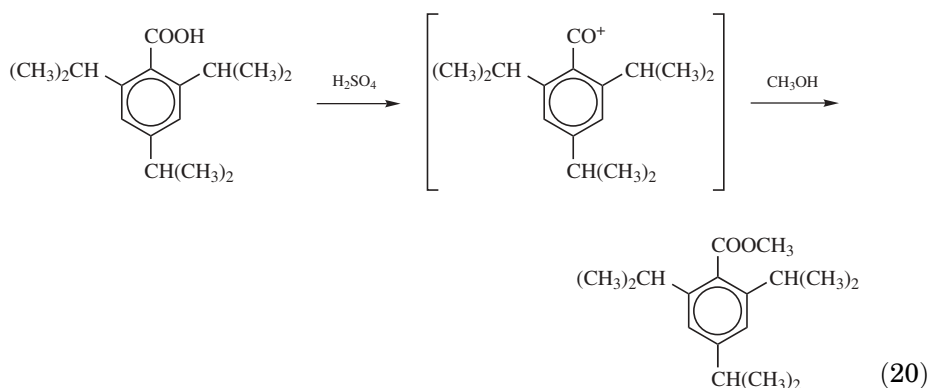
of carboxyl group. The mixture is refluxed for 6–15 h, although in some cases the time may be as short as 30 minutes. Progress of esterification is usually indicated by the development of cloudiness and separation of an upper layer containing water, methanol, and sulfuric acid. After the reaction is completed, the cooled mixture is washed successively with water, sodium bicarbonate solution, and again with water. The ethylene chloride layer is then distilled at atmospheric or reduced pressure, and the residual methyl ester is purified by distillation or crystallization.

The manufacture of high purity methyl acetate by a reactive distillation process has been accomplished; high conversion of one reactant can be achieved only with a large excess of the other reactant. Because the reaction is reversible, the rate of reaction in the liquid phase is increased by removing methyl acetate preferentially to the other components in the reaction mixture (100).

7.2. Medium Boiling Esters. Esterification of ethyl and propyl alcohols, ethylene glycol, and glycerol with various acids, eg, chloro- or bromoacetic, or pyruvic, by the use of a third component such as benzene, toluene, hexane, cyclohexane, or carbon tetrachloride to remove the water produced is quite common. Benzene has been used as a co-solvent in the preparation of methyl pyruvate from pyruvic acid (101). The preparation of ethyl lactate is described as an example of the general procedure (102). A mixture of 1 mol 80% lactic acid and 2.3 mol 95% ethyl alcohol is added to a volume of benzene equal to half that of the alcohol (ca 43 mL), and the resulting mixture is refluxed for several hours. When distilled, the overhead condensate separates into layers. The lower layer is extracted to recover the benzene and alcohol, and the water is discarded. The upper layer is returned to the column for reflux. After all the water is removed from the reaction mixture, the excess of alcohol and benzene is removed by distillation, and the ester is fractionated to isolate the pure ester.

7.3. High Boiling Esters. The following procedure can be used for making diethyl phthalate and other high boiling esters (103). Phthalic anhydride (1 equiv) and 2.5 equivalents of ethanol are refluxed for 2 h in the presence of 1% of concentrated H_2SO_4 . To produce the monoester, the excess of alcohol is distilled at $<100^\circ\text{C}$. For the diester, a mixture of 67% benzene and 33% alcohol is introduced continuously below the surface of the reaction mixture and the resulting alcohol–water–benzene ternary is distilled and condensed. A yield of diester of $>99\%$ is obtained by passing 3.4–7 equivalents of alcohol through the mixture in 4.5–7 hours. In another continuous process for the production of diesters, the mixture of alcohol, acid, and the catalyst is introduced into the upper part of a distillation column and an excess of the alcohol is introduced into the bottom. The column is heated so that the ester, water, and excess alcohol are distilled off (104). Organotitanates, zirconates, or organotin compounds are effective catalysts for the esterification of carboxylic acids or anhydrides with higher boiling monohydroxy alcohols at temperatures that permit the continuous distillation of the water formed (105). Refluxing 1 mol phthalic anhydride with 3 mol 2-ethyl-2-hexanol with stirring using these agents, then removing the water by a trap separator gives the corresponding esters in $\sim 99\%$ yields (see PHTHALIC ACID). Phthalic anhydride has been esterified with $>99\%$ conversion with 10–30% excess alcohol in the presence of 0.8–1.5 mol % alkyl titanate containing 0.08–0.2% activating agent in a vertical, multistage reactor connected to a devolatilization column and filter (106).

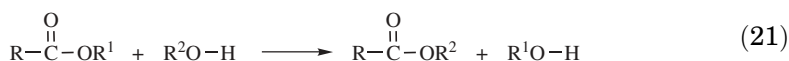
7.4. Difficulty Esterifiable Acids. The sterically hindered acids, such as 2,6-disubstituted benzoic acids, cannot usually be esterified by conventional means. Several esters of sterically hindered acids such as 2,4,6-triisopropylbenzoic acid [49623-71-4] have been prepared by dissolving 2 g of the acid in 14–20 mL of 100% H_2SO_4 (107). After standing a few minutes at room temperature, when presumably the acylium cation is formed (eq. 20), the solution is poured into an excess of cold absolute methanol. Most of the alcohol is removed under reduced pressure, about 50 mL of water is added, and the distillation is continued under reduced pressure to remove the remainder of the methanol. The organic matter is extracted with ether and treated with sodium carbonate solution. The ester is then distilled. Yields of esters made in this manner are 57–81%.



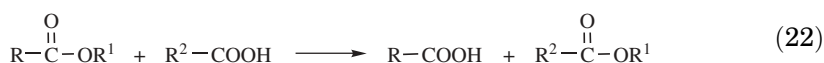
8. Ester Interchange

Ester interchange (transesterification) is a reaction between an ester and another compound, characterized by an exchange of alkoxy groups or of acyl groups, and resulting in the formation of a different ester. The process of transesterification is accelerated in the presence of a small amount of an acid or a base.

Three types of transesterification are known: (1) exchange of alcohol groups, commonly known as alcoholysis. In this process the compound with which an ester reacts is an alcohol:



(2) exchange of acid groups, acidolysis. In this process the compound with which an ester reacts is an acid:



(3) ester-ester interchange. In this process an exchange takes place between two esters:



These reactions are reversible and ordinarily do not involve large energy changes.

8.1. Ester-Alcohol Interchange. *Reaction Conditions.* Alcoholysis commonly takes place in one liquid phase, sometimes with one of the reactants being only partially soluble and going into solution gradually as the reaction proceeds. Unless an excess of one of the reactants is used, or unless one of the products is withdrawn from the reaction phase by vaporization or precipitation, the reaction does not proceed to completion but comes to a standstill with substantial proportions of both alcohols and both esters in equilibrium. The concentrations present at equilibrium depend on the characteristics of the alcohols and esters involved, but in most practical uses of the reaction, one or both of the devices mentioned are used to force the reaction toward completion.

Temperatures. With alkaline catalysts, the reaction often takes place at RT or even lower temperatures. With acid catalysts, temperatures near 100°C are commonly used. With no catalyst, temperatures ~250°C may be required for a practical reaction rate.

Catalysts. Of the alkaline catalysts, alkali metal alkoxides are the most effective; ordinarily, the sodium or potassium alkoxide of the alcohol entering the reaction is preferred. Various other catalysts of milder alkalinity are preferred in special cases. For example, the use of sodium methyl carbonate as catalyst in the methanolysis of poly(vinyl acetate) is said to yield a poly(vinyl alcohol) having improved color. Aluminum alkoxide has been proposed as a catalyst for the alcoholysis of certain unsaturated esters; other sensitive esters have been made with a Grignard reagent as catalyst. Zinc is reported to be an efficient catalyst in the alcoholysis of ethyl esters of α -halogenated aliphatic acids by allyl and methallyl alcohols; conventional catalysts favor undesirable side reactions. Neutral organic titanates have received much attention (108). Divalent metal salts such as zinc or manganese acetate and organotin compounds such as dibutyltin oxide have been employed.

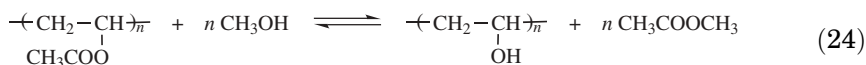
Among the acid catalysts, sulfuric acid, sulfonic acids, and hydrochloric acid are most used. With polyhydric alcohols, sulfuric acid is preferred to hydrochloric acid because of the tendency of hydrochloric acid to form chlorohydrins.

Equilibrium. In general, primary alcohols are more reactive than secondary alcohols (that is, they tend to displace them), and secondary alcohols tend to displace tertiary alcohols, but in addition, there are considerable differences among different members of the same class. Various alcohols have been compared in this way (4,109).

Applications. Transesterifications via alcoholysis play a significant role in industry as well as in laboratory and in analytical chemistry. The reaction can be used to reduce the boiling point of esters by exchanging a long-chain alcohol group with a short one, eg, methanol, in the analysis of fats, oils, and waxes. For more details see References 7 and 68. A few examples are given below.

n-Butyl Oleate. Olive oil, 3 kg, consisting mainly of the glyceryl esters of oleic acid, is refluxed for 20 h with 7 L of *n*-butyl alcohol containing 150 g of concentrated H_2SO_4 . The product contains a small proportion of saturated esters (110).

Poly(vinyl alcohol). Poly(vinyl alcohol) (see VINYL POLYMERS) is more easily prepared, in a form that can be filtered and washed in a practical way, by alcoholysis of poly(vinyl acetate), than by its saponification in an aqueous system:



The use of a catalytic quantity of alkali equivalent to only a small fraction of the acetate has the advantage that contamination of the poly(vinyl alcohol) with salts, which are difficult to remove, is minimized. A variant of the process is the use of a mixture of alcohol with the acetate ester produced by the alcoholysis as the alcoholyzing agent. This provides a means of controlling the completeness of removal of the acetate groups from the poly(vinyl acetate) (111).

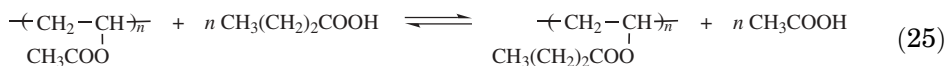
Acrylic Esters. A procedure has been described for preparation of higher esters from methyl acrylate that illustrates the use of an acid catalyst together with the removal of one of the products by azeotropic distillation (112). Another procedure for the preparation of butyl acrylate, secondary alkyl acrylates, and hydroxyalkyl acrylates using *p*-toluenesulfonic acid as a catalyst has been described (113). Aluminum isopropoxide catalyzes the reaction of amino alcohols with methyl acrylate and methyl methacrylate. A review of the synthesis of acrylic esters by transesterification is given in Reference 114 (see ACRYLIC ACID AND DERIVATIVES).

8.2. Ester–Acid Interchange. Acidolysis requires the use of an elevated temperature, the use of an acid catalyst (7), or both. Like alcoholysis, the reaction is reversible and requires the use of an excess of the replacing acid or removal of one of the products from the reaction if a high degree of replacement of the acid radical of an ester by another acid is to be obtained. This can be accomplished by distilling one of the products from the reaction mixture during the acidolysis.

In a series of organic acids of similar type, not much tendency exists for one acid to be more reactive than another. For example, in the replacement of stearic acid in methyl stearate by acetic acid, the equilibrium constant is 1.0. However, acidolysis in formic acid is usually much faster than in acetic acid, due to higher acidity and better ionizing properties of the former (115). Branched-chain acids, and some aromatic acids, especially sterically hindered acids such as ortho-substituted benzoic acids, would be expected to be less active in replacing other acids. Mixtures of esters are obtained when acidolysis is carried out without forcing the replacement to completion by removing one of the products. The acidolysis equilibrium and mechanism are discussed in detail in Reference 115.

An industrial example of acidolysis is the reaction of poly(vinyl acetate) with butyric acid to form poly(vinyl butyrate). Often a butyric acid–methanol

mixture is used and methyl acetate is obtained as a coproduct.



8.3. Ester–Ester Interchange. The reaction between two esters to produce two other esters was described by Friedel and Crafts in 1865, but has not been used as much as alcoholysis. The same general principles apply with regard to reversibility of the reaction and the means of driving the reaction to completion (7). In general, the same catalysts are effective as in alcoholysis. Usually the reaction is slower than alcoholysis of the same esters. Without a catalyst, a reaction time of several h at $>250^\circ\text{C}$ is required to bring two typical esters to equilibrium. Catalysts are almost essential to bring reaction rates into a practical range so that the use of destructive temperatures can be avoided. Tin compounds, especially stannous hydroxide, have been mentioned frequently as catalysts and do not produce much decomposition or discoloration of the esters (116). More effective at lower temperatures are the acid catalysts, such as sulfuric acid and sulfonic acids, and especially the alkaline catalysts such as sodium alkoxides. With an alkaline catalyst, ester–ester interchange can be carried out at temperatures as low as 0°C .

BIBLIOGRAPHY

“Esterification” in *ECT* 1st ed., Vol. 5, pp. 776–817, by C. E. Leyes, Celanese Corp. of America; “Ester Interchange” in *ECT* 1st ed., Vol. 5, pp. 817–823, by E. W. Eckey, E. W. Eckey Research Laboratory; “Esterification” in *ECT* 2nd ed., Vol. 8, pp. 313–356, by C. E. Leyes, Newark College of Engineering; “Ester Interchange” in *ECT* 2nd ed., Vol. 8, pp. 356–365 by E. W. Eckey, E. W. Eckey Research Laboratory, and E. F. Izard, E. I. du Pont de Nemours & Co., Inc.; “Esterification” in *ECT* 3rd ed., Vol. 9, pp. 291–310, by E. G. Zey, Celanese Corp.; in *ECT* 4th ed., Vol. 9, pp. 755–780, by M. Aslam, G. P. Torrence, and E. G. Zey, Hoechst Celanese Corporation.

CITED PUBLICATIONS

1. H. A. Goldsmith, *Chem. Rev.* **33**, 257 (1943).
2. D. B. Keyes, *Ind. Eng. Chem.* **24**, 1096 (1932).
3. E. E. Reid in E. E. Reid, *Unit Processes in Organic Synthesis*, 5th ed., McGraw-Hill Book Co., Inc., New York, 1958.
4. S. Patai, *The Chemistry of Carboxylic Acids and Esters*, Wiley-Interscience, New York, 1969.
5. H. H. Szmant, *Organic Building Blocks of the Chemical Industry*, Wiley-Interscience, New York, 1989.
6. M. L. Bender, *Chem. Rev.* **60**, 53 (1960).
7. K. S. Markley in K. S. Markley, ed., *Fatty Acids*, part 2, Wiley-Interscience, New York, 1961, p. 757.

8. J. March, *Advanced Organic Chemistry*, 3rd ed., John Wiley & Sons, Inc., New York, 1985.
9. R. C. Larock, *Comprehensive Organic Transformations*, VCH Publishers, Inc., New York, 1989.
10. *Chem. Eng. News* **69**, 28 (June 24, 1991).
11. B. Holmberg, *Chem. Ber.* **45**, 2997 (1912).
12. M. Polanyi and A. L. Szabo, *Trans. Faraday Soc.* **30**, 508 (1934).
13. E. K. Euranto in Ref. 4, p. 505.
14. R. C. Sharma and M. M. Sharma, *Bull. Chem. Soc. (Japan)* **43**, 642 (1970).
15. R. C. Sharma and M. M. Sharma, *J. Appl. Chem.* **19**, 162 (1969).
16. R. J. Hartman, L. B. Storms, and A. G. Gassmann, *J. Am. Chem. Soc.* **61**, 2167 (1939) and references therein.
17. A. G. Gassmann and R. J. Hartman, *J. Am. Chem. Soc.* **63**, 2393 (1941) and references therein.
18. M. Berthelot and L. Pean de Saint-Gilles, *Ann. Chim. Phys.* **68**, 225 (1863).
19. E. S. Gould, *Mechanisms and Structure in Organic Chemistry*, Holt, Rinehard, and Winston, New York, 1959, p. 314.
20. J. Hine, *Physical Organic Chemistry*, McGraw-Hill Book Co., Inc., New York, 1962, p. 275.
21. C. A. Lane, *J. Am. Chem. Soc.* **86**, 2521 (1964).
22. Y. K. Syrkin and I. I. Moiseev, *Usp. Khim.* **27**, 717 (1958).
23. V. A. Palm and co-workers, *Zh. Fiz. Khim.* **36**, 2499 (1962).
24. C. Murphy and co-workers, *Chem. Petro-Chem. J.* **10**(5), 13 (1979).
25. J. L. Guy, *Chem. Eng.* **89** (13), 97 (1982).
26. M. B. Bogacki and J. Szymanowski, *Pr. Nauk. Inst. Chem. Nieorg. Metal. Pierwiastkow Rzadkich Politech. Wroclaw.* **55**, 99 (1986); *Chem. Abstr.* **106**, 20447m (1986).
27. T. Yamada and Y. Imamura, *Polym.-Plast. Technol. Eng.* **28**(7-8), 811 (1989).
28. V. Parausanu and co-workers, *Rev. Chim. (Bucharest)* **31**(1), 30 (1980).
29. N. Schlechter, D. F. Othmer, and S. Marshak, *Ind. Eng. Chem.* **37**, 900 (1945).
30. C. E. Leyes and D. F. Othmer, *Ind. Eng. Chem.* **37**, 968 (1945).
31. S. Berman, A. A. Melnychuk, and D. F. Othmer, *Ind. Eng. Chem.* **40**, 1312 (1948).
32. M. Berthelot and P. Saint-Gilles, *Ann. Chim. Phys.* **65**, 385 (1862).
33. W. Swietoslawski, *J. Phys. Chem.* **37**, 701 (1933).
34. P. E. Coria, *Rev. Fac. Cienc. Quim. Univ. Nac. La Plata* **10**, 67 (1935).
35. C. A. Durruty, *An. Assoc. Quim. Argent.* **19**, 227 (1931).
36. H. M. Trimble and E. L. Richardson, *J. Am. Chem. Soc.* **62**, 3721 (1932).
37. W. P. Jencks and M. Gilchrist, *J. Am. Chem. Soc.* **86**, 4651 (1964).
38. Jpn. Pat. 62,096,453 (May, 1987), M. Hirata, K. Ishikawa, and S. Naruto (to Japan Organo Co., Ltd.).
39. L. H. Horsley in R. F. Gould, ed., *Azeotropic Data—III*, American Chemical Society, Washington, D.C., 1973.
40. J. C. Konen, E. T. Clocker, and R. P. Cox, *Oil Soap* **22**, 57 (1945).
41. E. Thielpape and A. Fulde, *Chem. Ber.* **B66**, 1454 (1933).
42. P. L. Gordon and R. Aronowitz, *Ind. Eng. Chem.* **37**, 780 (1945).
43. I. T. Harrison and S. Harrison, *Compendium of Organic Synthetic Methods*, Vol. 1, Wiley-Interscience, New York, 1971.
44. I. T. Harrison and S. Harrison, *Compendium of Organic Synthetic Methods*, Vol. 2, Wiley-Interscience, New York, 1974.
45. L. S. Hegedus and L. Wade, *Compendium of Organic Synthetic Methods*, Vol. 3, Wiley-Interscience, New York, 1977.
46. U.S. Pat. 4,833,267 (1989), S. Nakashima and co-workers (to Nippon Shokubai Kagaku Kogyo Co.).

47. S. S. Bhagade and G. D. Nageshwar, *Chem. Petro-Chem. J.* **9**(7), 3 (1978).
48. D. J. Pietrzyk, *Chromatogr. Sci.* **47**, 585 (1990).
49. Z. Gomzi and S. Zrncevic, *Croat. Chem. Acta.* **53**(1), 25 (1980).
50. *Chem. Abstr.* **110**, 137443f (1989).
51. WO 9,008,121 (1990), M. Wilmott and co-workers (to Davy McKee (London) Ltd.).
52. C. L. Levesque and A. M. Craig, *Ind. Eng. Chem.* **40**, 96 (1948).
53. M. J. Astel, B. Schaeffer, and C. O. Obenland, *J. Am. Chem. Soc.* **77**, 3643 (1955).
54. R. Neumann and Y. Sasson, *Ind. Eng. Chem. Process Des. Dev.* **23**, 654 (1984).
55. C. E. Leyes and D. F. Othmer, *Trans. Am. Inst. Chem. Eng.* **41**, 157 (1945).
56. U.S. Pat. 2,426,968 (Sept. 2, 1947), H. W. Grubb, L. M. O'Hara, and K. Atwood (to Seagram and Sons).
57. U.S. Pat. 4,374,070 (1983), T. Larkin, S. Polichnowski, and G. Tustin (to Eastman Kodak Co.).
58. U.S. Pat. 4,435,595 (1984), V. Agreda and L. Partin (to Eastman Kodak Co.).
59. V. Agreda, L. Partin, and W. Heise, *Chem. Eng. Prog.* **40** (1990) and references therein.
60. Brit. Pat. 2,033,385 (1980), C.-G. Wan (to Halcon Research and Development Corp.).
61. Eur. Pat. 87,870 (1983), J. B. Cooper (to British Petroleum Chem. Ltd.).
62. V. I. Goldanskii, *J. Phys. Chem. USSR* **21**, 431 (1947); H. C. Tidwell and E. E. Reid, *J. Am. Chem. Soc.* **53**, 4353 (1931).
63. A. Mailhe and F. deGodon, *Bull. Soc. Chim. Fr.* **29**, 101 (1921); G. Edgar and W. H. Schuyler, *J. Am. Chem. Soc.* **46**, 64 (1924).
64. H. F. Hoerig, D. Hanson, and O. L. Kowalke, *Ind. Eng. Chem.* **35**, 575 (1943).
65. A. M. Chashchin and N. M. Levedeva, *Gidroliz. Lesokhim. Promst.* **15**, 6 (1962).
66. S. Sharipova, A. Arifdzhanov, and A. Sultanov, *Katal. Pererab. Uglevodorodnogo Syrya*, 108 (1967).
67. J. F. Spangenberg, *Ind. Quim. Buenos Aires* **7**, 393 (1945).
68. C. A. Buehler and D. E. Pearson, *Survey of Organic Synthesis*, Wiley-Interscience, New York, 1970, p. 801.
69. A. van Es and W. Stevens, *Recl. Trav. Chim. Pays-Bas* **84**, 704 (1965).
70. S. Sofuku and co-workers, *Bull. Chem. Soc. Jpn.* **40**, 2942 (1967).
71. M. B. Shambhu and G. A. Digenis, *Tetrahedron Lett.*, 1627 (1973).
72. C. D. Hurd and A. S. Roe, *J. Am. Chem. Soc.* **61**, 3355 (1939).
73. N. O. V. Sonntag, *Chem. Rev.* **52**, 272 (1953).
74. W. H. Puterbaugh, *J. Org. Chem.* **27**, 4010 (1962).
75. S. Masamune and co-workers, *J. Am. Chem. Soc.* **97**, 3515 (1975).
76. W. J. Greenlee and E. D. Thorsett, *J. Org. Chem.* **46**, 5351 (1981).
77. S. G. Toole and F. J. Sowa, *J. Am. Chem. Soc.* **59**, 1971 (1937).
78. Ref. 43, p. 289.
79. J. S. Matthews and J. P. Cookson, *J. Org. Chem.* **34**, 3204 (1969).
80. E. H. White, *J. Am. Chem. Soc.* **77**, 6011 (1955).
81. Ref. 5, pp. 86 and 312.
82. J. A. John in S. A. Miller, ed., *Ethylene and Its Industrial Derivatives*, Ernest Benn Ltd., London, 1969, p. 765.
83. B. T. Brooks, *Ind. Eng. Chem.* **27**, 278 (1935).
84. U.S. Pat. 3,014,066 (Dec. 19, 1961), E. R. Kerr and M. C. Throckmorton (to Texaco).
85. W. Schwerdtel, *Hydrocarbon Process.* **47**, 187 (1968).
86. Brit. Pat. 981,987 (Feb. 3, 1955), (to Farbenfabriken Bayer AG).
87. E. J. Corey and L. S. Hegedus, *J. Am. Chem. Soc.* **91**, 1233 (1969).
88. B. Ganem and V. R. Small, *J. Org. Chem.* **39**, 3728 (1974).
89. E. C. Juenge and D. A. Beal, *Tetrahedron Lett.*, 5819 (1968).
90. M. H. Karger and Y. Mazur, *J. Org. Chem.* **36**, 532 (1971).

91. J. N. Marx and J. Sondheimer, *Tetrahedron (suppl. 8, part 1)*, 1 (1966).
92. U.S. Pat. 3,652,647 (Mar. 28, 1972), E. G. Zey (to Celanese).
93. M. Y. Kagen and I. A. Sobolev, *J. Chem. Ind. (Moscow)* (2), 35 (1933).
94. J. Houben and W. Fisher, *Chem. Ber.* **B64**, 240 and 2636 (1931).
95. H. O. House, *Modern Synthetic Reactions*, 2nd ed., W. A. Benjamin, Inc., Menlo Park, Calif., 1972, 321–326.
96. Ref. 82, p. 764.
97. H. Gilman, ed., *Organic Synthesis*, Vol. 1, John Wiley & Sons, Inc., New York, 1932, 138–140.
98. S. O. Nwauka and P. M. Keehn, *Tetrahedron Lett.* **23**, 35 (1982).
99. R. O. Clinton and S. C. Laskowski, *J. Am. Chem. Soc.* **70**, 3135 (1948).
100. U.S. Pat. 4,939,294 (July 3, 1990), V. H. Agreda and R. D. Lilly (to Eastman Kodak Co.).
101. A. Weissberger and C. J. Kibler, *Organic Synthesis Coll.* Vol. 3, John Wiley & Sons, Inc., New York, 1955, p. 610.
102. U.S. Pat. 1,421,604 (July 4, 1922), J. A. Steffens (to U.S. Industrial Alcohol Co.).
103. U.S. Pat. 2,076,111 (Apr. 6, 1927), W. J. Bannister (to Commercial Solvents Corp.).
104. Ger. Pat. DE 878,348 (1942), H. Dierichs and co-workers (to BASF).
105. Brit. Pat. 852,110 (Oct. 26, 1960), (to B. F. Goodrich Co.).
106. Rom. Pat. 66,492B (Oct. 20, 1979), I. Drimus and E. D. Morath (to binatul Petro-chemic "Solventul").
107. M. S. Newman, *J. Am. Chem. Soc.* **63**, 2431 (1941).
108. *TYZOR Organic Titanates*, *Du Pont Bulletin D5258*, E. I. du Pont de Nemours & Co., Inc., Wilmington, Del., 1972, 5M. Rev. 377.
109. G. B. Hatch and J. E. Adkins, *J. Am. Chem. Soc.* **59**, 1694 (1937).
110. E. E. Reid and co-workers in A. H. Blatt, ed., *Organic Synthesis*, Coll. Vol. 2, John Wiley & Sons, Inc., New York, 1943, p. 469.
111. U.S. Pat. 2,266,996 (Dec. 23, 1941), N. D. Scott and J. E. Bristol (to E.I. du Pont de Nemours & Co., Inc.).
112. C. E. Rehberg and C. H. Fisher, *J. Am. Chem. Soc.* **66**, 1203 (1944).
113. C. E. Rehberg, *Organic Synthesis*, Coll. Vol. 3, John Wiley & Sons, Inc., New York, 1955, p. 146.
114. J. K. Haken, *Synthesis of Acrylic Esters by Transesterification*, Noyes Development Corp., Park Ridge, N.J., 1967.
115. J. Koskikallio in S. Patai, ed., *The Chemistry of Carboxylic Acids and Esters*, Wiley-Interscience, New York, 1969, 103–136.
116. A. E. Bailey, *Industrial Oil and Fat Products*, Interscience Publishers, New York, 1945, p. 676.

MOHAMMAD ASLAM
G. PAULL TORRENCE
EDWARD G. ZEY
Hoechst Celanese Corporation