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PURIFICATION OF SOLVENTS
FOR ELECTROANALYSIS:
TETRAHYDROFURAN AND DIOXANE

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Purification of solvents for electroanalysis: tetrahydrofuran and dioxane

This report is a continuation of the same project of the Commission on Electroanalytical Chemistry which led to the publication in 1982 of the compilation Recommended Methods for Purification of Solvents and Tests for Impurities (Pergamon Press) in which ten protic and aprotic solvents are discussed. The present report is the first to deal with the important class of saturated cyclic ethers, solvents that are used extensively in organometallic chemistry and battery technology. Key properties and uses of these solvents are briefly outlined. In the discussion of recommended purification methods and tests for impurities special emphasis is placed on the presence of peroxides which constitutes a serious explosion hazard in the handling of many ethers.

INTRODUCTION

Tetrahydrofuran (I) and dioxane (1,4-dioxane, p-dioxane) (II) are important members of the

(I)   (II)   (III)   (IV)   (V)
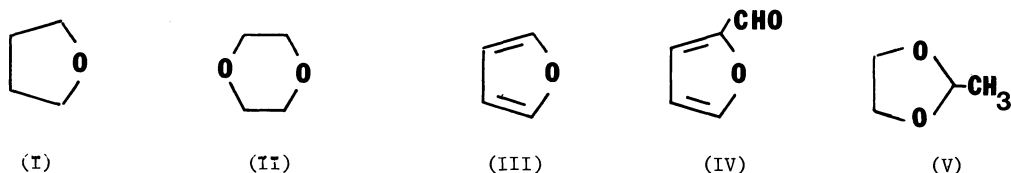
class of saturated cyclic ethers which owe their utility to a fortuitous combination of properties, some of which are listed in Table 1. In particular, both liquids are miscible in all proportions not only with many organic solvents but, in spite of their comparatively low relative permittivities (dielectric constants), also with water. Especially in the case of dioxane-water mixtures, this property has allowed numerous important physicochemical studies of electrostatic effects in electrolyte solutions over a wide range of relative permittivities ($2.2 < D < 78.5$). Both compounds also have important industrial uses. For example, tetrahydrofuran is used as a solvent for polyvinyl chloride in printing inks, lacquers and adhesives, as well as an intermediate in the preparation of many industrial chemicals, e.g., by polymerization to polymethylene ether glycol, $H + O-(CH_2)_4 +_n OH$, which is used in polyurethane technology (Ref. 5.a). Dioxane is used as a solvent for natural resins and cellulose acetate, and it is an ingredient in numerous commercial formulations, e.g., in printing inks, paint removers and detergents. Its remarkable property of dissolving both water and paraffin wax is used to advantage in the preparation of histological sections for microscopic examination (Ref. 5.b).

The commercial preparation of tetrahydrofuran is carried out by catalytic hydrogenation of furan (III), which is obtained by catalytic decarbonylation of furfural (IV), which in turn is prepared by digesting such pentosan-containing agricultural residues as corncobs with dilute sulfuric acid (Ref. 5.a). Dioxane may be manufactured by several methods, including dehydration of ethylene glycol with sulfuric acid and heating ethylene oxide or bis(β-chloroethyl) ether with sodium hydroxide.

KEY SOLVENT PROPERTIES OF TETRAHYDROFURAN AND DIOXANE

The important property of complete miscibility of both tetrahydrofuran and dioxane with many organic solvents as well as water has led to a vast literature dealing with the properties and applications of such solvent mixtures. Various physical properties of mixtures of dioxane with water, methanol and ethanol have been tabulated; references are given in Ref. 5.b. Both tetrahydrofuran and dioxane form azeotropes with water; compositions are 4.3% and 18.4% water, respectively.

Dioxane can exist in chair and boat conformations. The chair form is favored at lower temperatures, so that the dipole moment becomes negligible at temperatures below ca. 20°C (Ref. 3).

TABLE 1. Selected properties and parameters of tetrahydrofuran (THF) and dioxane

Property	THF	Dioxane
Freezing temperature, T/K −273.15 ($t_m/°C$)	−108.5	11.80
Boiling temperature at 101.325 kPa (1 atm), T/K −273.15 ($t_b/°C$)	66	101.32
Flash point (closed cup), $t_{fl}/°C$	− 14	12
Vapor pressure at 25°C, p/kPa	26.0	4.9
Density, $\rho/kg\ dm^{-3}$	0.8892 (20°C)	1.02797 (25°C)
Dynamic viscosity, $\eta/mPa\ s$	0.460 (25°C)	1.087 (30°C)
Surface tension, $\gamma/mN\ m^{-1}$	26.4 (25°C)	32.2 (30°C)
Enthalpy of vaporization at t_b, $\Delta H_v/kJ\ mol^{-1}$	29.58	35.58
Molar heat capacity, $C_p/J\ K^{-1}\ mol^{-1}$	141.4 (20°C)	153.0 (18°C)
Refractive index at 25°C, n_D	1.40496	1.42025
Dipole moment at 25°C, μ/D	1.75 (benzene)	0.45
Relative permittivity (dielectric constant) at 25°C, $D = \varepsilon/\varepsilon_0$	7.58	2.21
Donor number, Gutmann, at 25°C, $DN/kcal\ mol^{-1}$	20.0[a]	14.8[a]
Acceptor number, Mayer–Gutmann, at 25°C, AN (dimensionless)	8.0	10.8
Solvatochromic parameters, Kamlet-Taft, at 25°C		
--polarity parameter, π^*	0.58	0.55
--hydrogen bond acceptor parameter, β	0.55	(0.37)[b]

Donor and acceptor numbers are from Ref. 1, solvatochromic parameters are from Ref. 2, and values of properties are from Ref. 3.

[a] 1 cal = 4.184 J.

[b] Uncertain; also see Ref. 4.

The relative basicities of different cyclic ethers vary, as expected, with the nature of the reference acid. For example, with hydronium ion as reference acid (in aqueous sulfuric acid), Arnett and Wu (Ref. 6) found the basicity order THF > 2-MeTHF > dioxane (pK_a = -2.08, -2.65 and -3.22, respectively). The same order of THF > dioxane is found with antimony pentachloride as reference acid in 1,2-dichloroethane as solvent, as shown by the donor numbers in Table 1, as well as with various solvatochromic indicators as reference hydrogen bond donors, as shown by the Kamlet-Taft β-parameters in Table 1. On the other hand, Goldman et al. (Ref. 7) found the reverse basicity order of THF < 2-MeTHF towards lithium ion as reference acid.

Tetrahydrofuran and dioxane behave as typical aprotic solvents in that they are weak solvators of anions with localized and/or multiple charges. On the other hand, both solvents (but particularly tetrahydrofuran) are relatively strong solvators of cations through interactions with their oxygen atoms. One result is that the solubilities of such salts as LiA, where A = ClO_4, BF_4, AsF_6 etc., are quite high (> 1 M) in tetrahydrofuran, although such solutions contain a preponderance of ion pairs and higher aggregates.

Tetrahydrofuran is an exceptionally useful solvent for reactions with organoalkali compounds (Ref. 8). It also dissolves the alkali metals (M), with the exception of lithium, with the formation of M^+ and solvated electrons as well as M^- ions (Ref. 9). Such solutions have been extensively studied by optical and resonance spectroscopy and other probes (Ref. 10). Tetrahydrofuran and especially its 2-methyl derivative are also useful solvents for rechargeable high energy density batteries such as $Li|Li^+AsF_6^-$ in THF$|TiS_2$ (Ref. 11).

Dioxane is a useful solvent for perchloric acid as titrant.

TESTS FOR IMPURITIES IN COMMERCIAL TETRAHYDROFURAN AND DIOXANE

Reagent grades of dioxane obtained from different suppliers generally conform to ACS speci-
fications (Ref. 12) which include the following categories. (a) Freezing temperature,
$\geq$ 11.0°C; (b) water, $\leq$ 0.05%; (c) carbonyls (as HCHO), determined by adding hydrazine and
measuring the resulting hydrazone polarographically, $\leq$ 0.01%; (d) neutrality (actually bas-
icity), determined by titration with perchloric acid in dioxane to the methyl violet end
point, $\leq$ 2 x 10^{-4} eqv/L base (mol H^+/L base); and peroxides (as H_2O_2), $\leq$ 0.005% (see below).
Additional specifications for maximum concentrations of impurities in a typical reagent grade
of dioxane (Fisher Certified ACS) are these: acidity (as CH_3COOH), 0.01%; heavy metals (as
Pb), 0.25 ppm ($\mu g/g$); and iron, 0.25 ppm. There are no ACS specifications for tetrahydro-
furan, but a typical reagent grade (Fisher Certified) carries the following specifications
for maximum concentrations of impurities: water, 0.02%, and peroxides (as THF peroxide),
0.015%; in addition, ca. 0.025% of "butylated hydroxytoluene" has been added as inhibitor
(stabilizer, preservative) to prevent peroxide formation.

Peroxides in Ethers

Virtually all ethers react with oxygen to form peroxides; the reaction is accelerated by
light, heat and moisture. The peroxides are explosive and may detonate violently on adding
such reactive substances as solid potassium hydroxide or lithium aluminum hydride to the
ether, on heating the ether (especially to dryness), and on creating friction, e.g., by
loosening or tightening the cap of the container (Ref. 13). Consequently, it is essential to
take special precautions in the storage, handling and distillation of ethers; such precau-
tions have been described by Steere (Ref. 13). It is particularly important to exercise
caution with any ether from which the inhibitor has been removed, e.g., by distillation; such
ether must be stored in the dark under dry argon or nitrogen.

Tests for Peroxides

Peroxides can be detected and determined in ethers with iodide ion (Ref. 13), with iron(II)
ion plus thiocyanate ion, or with titanium(IV). The following procedure is recommended by
the American Chemical Society (Ref. 12) for the determination of peroxide in dioxane.

> Dilute 10.0 mL of dioxane with water to 50 mL and treat 5.0 mL of the resulting
> solution with 5.0 mL of titanium tetrachloride reagent (see below). Allow to
> stand for 5 ± 1 minutes, then measure the optical absorbance at 410 nm.
> Treat standard solutions of hydrogen peroxide in water similarly.

> The titanium reagent is prepared as follows. Cool separately in small beakers
> surrounded by crushed ice 10 mL of 20% hydrochloric acid and 10 mL of
> water-white titanium tetrachloride. Add the titanium salt dropwise with
> stirring to the acid. Allow the mixture to stand at ice temperature until all
> of the initially precipitated yellow solid dissolves, then dilute the solution
> to 1 L with 20% hydrochloric acid.

Removal of Peroxides

Fortunately, peroxides present in ethers can easily be destroyed. Numerous reducing agents
have been used for this purpose, including activated carbon, sodium bisulfite, iron(II)
sulfate, tin(II) chloride and cerium(III) hydroxide (Ref. 3, 13). Alternatively, a con-
venient method is to pass the ether through a column packed with an anion exchange resin such
as Dowex-1 (Ref. 13) in the OH^- form, or with activated basic alumina (Ref. 3), or (pre-
ferably) with NaX-type zeolite (Ref. 14).

Inhibition of Peroxide Formation

A variety of compounds act as inhibitors to peroxidation of ethers (Ref. 3); examples are
polyamines such as triethylenetetramine, N-benzyl-p-aminophenol, and "butylated hydroxy-
toluene" which is used commercially in tetrahydrofuran. Hamstead and VanDelinder (Ref. 15)
have discussed the utility of such additives in the context of theories of autoxidation of
ethers with emphasis on the stabilization of isopropyl ether which is especially prone to
peroxidation.

Removal of Water

Burfield et al. (Ref. 16, 17) have made a critical study of the efficiency of various desic-
cants in a number of solvents, including tetrahydrofuran and dioxane. Among the most ef-
ficient are sodium metal, calcium hydride, and molecular sieves, particularly 3A-sieves
activated by heating at 250°C for 24 hours.

Other Impurities

Tetrahydrofuran may contain a variety of impurities in addition to water and peroxide; e.g., on aging it produces butyric acid and butyraldehyde as well as their 4-hydroxy derivatives and other related compounds (Ref. 3). Dioxane also may contain aldehydes (removed by boiling with silver oxide), as well as acetic acid and glycol acetal (V). The acetal is removed by heating the dioxane over sodium metal or, when present in relatively high concentrations, by refluxing the dioxane with 10% of its volume of 1 M hydrochloric acid for several hours while passing a slow stream of air (better: argon or nitrogen) through the condenser to remove the acetaldehyde formed (Ref. 18).

PURIFICATION OF TETRAHYDROFURAN AND DIOXANE

Numerous procedures have been recommended for the purification of these solvents, typically involving some type of pretreatment followed by distillation from such reagents as sodium metal, sodium-potassium alloy, potassium hydroxide and sodium metal, and, in the case of tetrahydrofuran, also calcium hydride, lithium aluminum hydride, and anthracene or benzo-phenone plus sodium metal (Ref. 3, 18). In the case of dioxane, fractional freezing (including zone refining) has also been used. A number of exceptionally elaborate procedures have been described; typical of these are procedures for the purification of tetrahydrofuran and dioxane intended as solvents for organometallic chemistry (Ref. 19) and of dioxane intended for kinetic studies monitored by ultraviolet spectrophotometry (Ref. 20).

Quite generally, the purification of solvents should be tailored to their intended use.

We recommend the following procedure for the purification of both tetrahydrofuran and diox-ane. In spite of its simplicity it is satisfactory for many purposes. It is to be under-stood, however, that additional steps may have to be included when the solvent is intended for unusual applications.

Step 1. Dry the solvent by passing it slowly through a column packed with 3A molecular sieves activated by heating at 250°C for 24 h (20 g/L).

Step 2. Remove peroxides (and many other impurities as well) by passing the effluent slowly through a column packed prefer-ably with type NaX zeolite (pellets ground to 0.1-mm size) activated by heating at 400°C for 24 h, or else with chroma-tographic grade basic alumina activated by heating at 250°C for 24 h (20 g/L).

Step 3. Test for the absence of peroxides with titanium tetrachlo-ride (see above) or with aqueous potassium iodide--starch reagent. CAUTION: Do not proceed with Step 4 unless the test for peroxides is negative!

Step 4. Reflux the effluent from Step 2 for several hours over sodium wire (10 g/L) while excluding atmospheric moisture; if nec-essary, add more sodium from time to time until the surface of the added metal remains shiny and clean.* Finally, dis-till the solvent under high reflux ratio and under an atmos-phere of dry argon or nitrogen, collecting the middle 80% cut. Store the product in full containers in the dark. Dispense the solvent by dry argon or nitrogen pressure.

*For dioxane, formation of a brown crust on the sodium indicates the presence of excessive amounts of glycol acetal, necessitating pretreatment with hydrochloric acid (see above).

SAFETY CONSIDERATIONS

While tetrahydrofuran is only moderately toxic (threshold limit in air: 200 ppm), it does form explosive mixtures with air in concentrations between 1.8 and 11.8% (v/v). Dioxane is much more toxic. Its threshold limit in air is 100 ppm, but it can also be absorbed through the skin. Its toxic effects include irritation to the eyes, nose and throat and, for large exposures, damage to the liver and kidneys. It also forms flammable mixtures with air in concentrations between 2 and 22% (v/v). Finally, the serious explosion hazard of both tetrahydrofuran and dioxane when they have been contaminated by peroxidation (which is par-ticularly likely when inhibitors have been removed by purification and when light and moist-ure have been present) should be reiterated.

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