

## Review of Safety Guidelines for Peroxidizable Organic Chemicals

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**There is a great deal of uncertainty regarding the hazards and safe handling of peroxidizable organic chemicals. No definitive data are available about the concentration at which adventitious peroxides pose a hazard. Some common chemicals (e.g., 2-propanol) have been shown to form potentially explosive concentrations of peroxides but are rarely included as part of peroxide safety programs. Several common peroxide detection methods used in safety programs may not detect all types of unstable peroxides. Similarly, some common deperoxidation procedures may not remove all types of unstable peroxides. Recommended administrative controls (e.g., shelf life restrictions) vary widely among authors. There are no specific federal OSHA regulations that pertain to the handling of peroxidizable organic chemicals. In this article, I review peroxide chemistry; the various classes of peroxide formers; hazardous levels of peroxides; and methods for control, detection, and removal of peroxides.**

Organic peroxides are carbon-based chemical compounds that contain the characteristic peroxide oxygen-oxygen bond. The primary types of organic peroxides are hydroperoxides (R-O-O-H) and dialkyl peroxides (R-O-O-R<sub>1</sub>, where R and R<sub>1</sub> are alkyl moieties). Several other types of peroxides exist, including acylperoxides, polyperoxides, peroxyesters, alkylidene peroxides, peroxyacids, and cyclic peroxides.

Most organic peroxides are, to varying degrees, shock, heat, or friction sensitive (1). Shock, shaking, friction, or heating of the liquid may cause an explosion. Whereas the reactive hazard of organic peroxide reagents (i.e., purchased or synthesized organic peroxides) is usually well known, the accumulation of adventitious organic peroxides in common solvents may lead to an unrecognized explosion hazard (2-4). Unexpected explosions involving peroxidized organic chemicals have been reported in the literature many times. Although peroxidizable chemical hazards are usually associated with laboratories, such chemicals are widely used in many types of industry and operations.

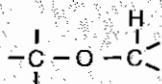
### Peroxidation chemistry

A wide variety of organic compounds spontaneously form peroxides by a free-radical reaction of the hydrocarbon with molecular oxygen in a process of autoxidation. The reaction can be initiated by light (photoperoxidation) or by a contaminant. Like other free-radical reactions, it is self-propagating, and one initiating event may form many peroxide molecules (1).

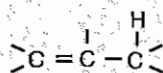
Although ethers are the most notorious peroxide formers, other peroxidizable organic moieties include acetals, certain allylic alkenes (olefins), chloro- and fluoroalkenes, dienes, aldehydes, amides, lactams, ureas, some alkylarenes, ketones, vinyl monomers, and some alcohols. Figure 1 presents peroxidizable moieties in order of decreasing hazard (2, 3, 5, 6). Obviously, it is an extensive list, and not all chemicals that fall into these categories have been shown to form potentially dangerous peroxides. This is a part of the problem that must be addressed when developing a control program for peroxidizable chemicals.

Peroxidation is most likely to occur in compounds with activated hydrogen atoms in which the intermediate free radical can be stabilized through resonance or a similar mechanism (1, 6, 7). For example, activated hydrogen atoms occur on carbon atoms linked by oxygen as ethers, on tertiary carbon atoms (e.g., the central carbon in isopropyl alcohol), on carbon atoms in vinyl structures, and in allylic and benzylic structures (i.e., on carbon atoms adjacent to vinyl or phenyl moieties). As a rule, a chemical containing more than one of these susceptible structures is at particular risk of peroxidation (4). For example, vinyl groups that are further activated by the addition of an attached halogen atom, a phenyl or carbonyl moiety, or another unsaturation are very susceptible to peroxidation (6).

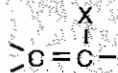
There is some controversy about the hazardous peroxidizability of simple primary alcohols, which lack an activated hydrogen atom (1, 5, 7-9). At present, most data do not suggest that such compounds, including ethanol, 1-propanol, 1-butanol, 1-pentanol, 1-heptanol, and 1-octanol, form hazardous peroxides. In contrast, the secondary alcohol 2-propanol (isopropanol), which possesses an activated hydrogen, will form concentrations of peroxides up to 4.2%,

1. Ethers and acetals with  $\alpha$ -hydrogen

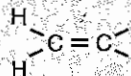
## 2. Alkenes with allylic hydrogen



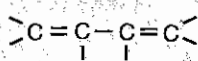
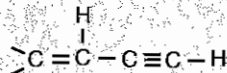
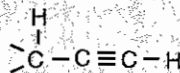
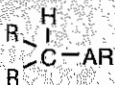
## 3. Chloroalkenes, fluoroalkenes



## 4. Vinyl halides, esters, ethers



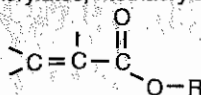
## 5. Dienes

6. Vinylalkynes with  $\alpha$ -hydrogen7. Alkylalkynes with  $\alpha$ -hydrogen8. Alkylarenes with tertiary  $\alpha$ -hydrogen

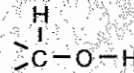
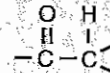
## 9. Alkanes and cycloalkenes with tertiary hydrogen



## 10. Acrylates, methacrylates



## 11. Secondary alcohols

12. Ketones with  $\alpha$ -hydrogen

## 13. Aldehydes

14. Ureas, amides, and lactams with  $\alpha$ -hydrogen atom on a carbon attached to nitrogen

Figure 1. Peroxidizable organic moieties, numbered from most (1) to least (14) likely to form dangerous peroxides.

and 2-butanol will form a 12% peroxide solution. Explosions involving these peroxidized alcohols have caused serious injuries (8–10). It is important to note, however, that primary alcohols with special structures that result in activation of hydrogen may be peroxidized. For example, 2-methylpropanol, 3-methylbutanol, 2-phenylethanol, and 2-ethylbutanol all have activated hydrogen, and all have been shown to be peroxidizable (8).

The rate of peroxidation is a function of the parent chemical. Of common laboratory ethers, tetrahydrofuran (THF) probably has the highest rate of peroxide formation (11). However, it is clear that the rate of peroxidation alone does not determine the degree of hazard posed by the chemical. A combination of factors, including the rate of peroxidation, the maximum peroxide concentration, volatility of the parent compound, and reactivity of the peroxides formed, determine the actual risk.

The risk of hazardous peroxidation generally decreases as the molecular weight of the compound increases. Ten or more carbon atoms at a peroxidizable site are considered low-risk systems (3). Dialkyl ethers ( $\text{R-O-R}_1$ ) are almost all susceptible to peroxidation, whereas diaryl ethers ( $\text{AR-O-AR}$ ) are generally much less susceptible. The National Safety Council states that diaryl ethers with no hydrogen atoms on either oxygen-linked carbon atom need not be treated as peroxide formers (3).

Peroxide accumulation is a balance between the formation of peroxide and degradation or further reaction of the peroxide. Peroxides are less volatile than the parent compound, and thus they concentrate as the parent chemical evaporates. Peroxidation may be accelerated by exposure to heat, light, and oxygen or air. Storing chemicals in open, partially empty, or transparent containers and at elevated temperatures may promote peroxidation. The effects of light and heat

are somewhat variable and unpredictable, but the effect of exposure to oxygen is always to increase the formation of peroxides. Intentional or incidental contamination of peroxidizable alcohols with ketones may photosensitize the alcohol and exacerbate the effect of light exposure (10, 12). Similar interactions may occur that have not been documented.

Generally, it is recommended that volatile organic peroxidizables be refrigerated to slow oxidation. However, peroxide accumulation may actually be enhanced by refrigeration, as the rate of peroxide degradation is slowed more than is the rate of peroxide formation. This is known to be true for some peroxidizable organometallic compounds, which thus should not be refrigerated (3). There is little or no evidence that refrigeration slows oxidation of diethyl ether, and the extreme volatility of this liquid means that a leak may form an explosive atmosphere, even in deep freeze (flash point  $-45^\circ\text{C}$ ) (6). Also, excess cooling, approaching the freezing point of the chemical, may cause the precipitation of peroxides from solution, which makes the container very shock sensitive and dangerous. Thus, refrigeration of volatile peroxide formers is a double-edged sword. In any case, only completely spark-proof refrigerators should be used to store ethers or other volatile peroxide formers.

Hydroperoxides are usually the initial product of autoxidation. However, over time, hydroperoxides may react further to form dialkyl, polymeric, cyclic, and other "higher" peroxides (1). This result is important because these secondary reaction products are more difficult to detect and remove than simple hydroperoxides (6, 11). The common peroxide tests are only sensitive to hydroperoxides and may yield a false negative or low result when higher peroxides are present. *p*-Dioxane, in particular, has been reported to form very significant levels (more than 30% of total peroxide) of diperoxide products (11). Isopropyl ether forms a variety of

**Table 1. Classes of peroxidizable chemicals**

<b>A. Chemicals that form explosive levels of peroxides without concentration</b>			
Butadiene <sup>a</sup>	Divinylacetylene	Tetrafluoroethylene <sup>a</sup>	Vinylidene chloride
Chloroprene <sup>a</sup>	Isopropyl ether		
<b>B. Chemicals that form explosive levels of peroxides on concentration</b>			
Acetal	Diacetylene	2-Hexanol	2-Phenylethanol
Acetaldehyde	Dicyclopentadiene	Methylacetylene	2-Propanol
Benzyl alcohol	Diethyl ether	3-Methyl-1-butanol	Tetrahydrofuran
2-Butanol	Diethylene glycol dimethyl ether	Methylcyclopentane	Tetrahydronaphthalene
Cumene	(diglyme)	Methyl isobutyl ketone	Vinyl ethers
Cyclohexanol	Dioxanes	4-Methyl-2-pentanol	Other secondary alcohols
2-Cyclohexen-1-ol	Ethylene glycol dimethyl ether	2-Pentanol	
Cyclohexene	(glyme)	4-Penten-1-ol	
Decahydronaphthalene	4-Heptanol	1-Phenylethanol	
<b>C. Chemicals that may autopolymerize as a result of peroxide accumulation</b>			
Acrylic acid <sup>b</sup>	Chlorotrifluoroethylene	Vinyl acetate	Vinylidene chloride
Acrylonitrile <sup>b</sup>	Methyl methacrylate <sup>b</sup>	Vinylacetylene	
Butadiene <sup>c</sup>	Styrene	Vinyl chloride	
Chloroprene <sup>c</sup>	Tetrafluoroethylene <sup>c</sup>	Vinylpyridine	

higher peroxides, including cyclic peroxides of acetone, which may be particularly explosive (13).

### Classes of peroxide formers

For some chemicals, the concentration of peroxide reaches dangerous, shock-sensitive levels without concentration. Other chemicals do not usually accumulate potentially explosive concentrations of peroxides unless the volatile organic material is reduced in volume. Such reduction may occur through incidental evaporation for very volatile compounds (e.g., diethyl ether) or through distillation (2, 3, 8). Distillation of peroxide-containing organic compounds has resulted in many serious accidents.

Part A of Table 1 (2, 3) lists representative chemicals that may form explosive concentrations of peroxides without concentration by evaporation or distillation. Indeed, some of these may form explosive concentrations of peroxides even if never opened. Part B lists chemicals that accumulate peroxides but that usually become hazardous only if evaporated or distilled or otherwise treated to concentrate the peroxides. Note that the most common laboratory peroxidizable chemicals, including diethyl ether, THF, cyclohexene, the glycol ethers, and 2-propanol (isopropyl alcohol), usually require some concentration to generate hazardous concentrations of peroxides. However, many of these chemicals are quite volatile, and repeated use of a container may allow enough evaporation to occur to concentrate peroxides to explosive levels. Part C lists certain peroxidizable vinyl monomers that may exothermically polymerize as a result of decomposition of accumulated peroxides; that is, the peroxides initiate very energetic polymerization of the bulk monomer. Part D lists other peroxidizable chemicals that have not been clearly characterized and thus have not been included in Parts A–C.

If properly packaged in manufacturing, peroxidizable pressurized gases such as butadiene, tetrafluoroethylene, vinylacetylene, and vinyl chloride should be relatively resis-

tant to autoxidation. However, these gases are sometimes transferred from the manufacturer's cylinder to another container in the laboratory, and it is difficult to completely eliminate residual air from the receiving vessel. An inhibitor should be placed in the receiving container before transfer is accomplished. The hazard of peroxidation may become much greater if these gases are condensed inside the cylinder or secondary vessel. All processes involving these gases should be thoroughly evaluated to determine the likelihood of forming a liquid phase (6).

### Hazardous levels of peroxides

Various sources suggest that the minimum hazardous concentration of peroxides in solution in organic chemicals is in the range 0.005–1.0% (50–10,000 ppm) as hydrogen peroxide (2, 3, 9, 11, 13). It has not been possible to reconcile this broad range (more than 2 orders of magnitude) because none of the authors cited provide any direct reference or data to support their statements. The high value (1.0%) is quoted from the National Safety Council (3), but the council provides no references to support this statement and recommends an administrative control value of 100 ppm. A University of California at Davis chemical safety document states, "There is not even agreement as to what concentration of peroxides constitutes a hazard" (14). One reference states that, with respect to distillation of the easily oxidized isopropyl ether, "The temperature and concentration at which explosion becomes probable has never been authoritatively stated. Even very small concentrations may be dangerous, since it is concentrated in the still system" (13). The Canadian Centre for Occupational Health MSDS for diethyl ether suggests that when the concentration of peroxide exceeds 100 ppm, a hazard may arise if the solution is concentrated (15). Presumably, as it concentrates it becomes more and more unstable. At some point, the solution spontaneously explodes.

**D. Chemicals that may form peroxides but cannot clearly be placed in sections A—C**

Acrolein	<i>tert</i> -Butyl methyl ether	Di(1-propynyl) ether <sup>d</sup>	4-Methyl-2-pentanone
Allyl ether <sup>d</sup>	<i>n</i> -Butyl phenyl ether	Di(2-propynyl) ether	<i>n</i> -Methylphenetole
Allyl ethyl ether	<i>n</i> -Butyl vinyl ether	Di- <i>n</i> -propoxymethane <sup>d</sup>	2-Methyltetrahydrofuran
Allyl phenyl ether	Chloroacetaldehyde diethylacetal <sup>d</sup>	1,2-Epoxy-3-isopropoxypropane <sup>d</sup>	3-Methoxy-1-butyl acetate
<i>p</i> -( <i>n</i> -Amyloxy)benzoyl chloride	2-Chlorobutadiene	1,2-Epoxy-3-phenoxypropane	2-Methoxyethanol
<i>n</i> -Amyl ether	1-(2-Chloroethoxy)-2-phenoxyethane	<i>p</i> -Ethoxyacetophenone	3-Methoxyethyl acetate
Benzyl <i>n</i> -butyl ether <sup>d</sup>	Chloroethylene	1-(2-Ethoxyethoxy)ethyl acetate	2-Methoxyethyl vinyl ether
Benzyl ether <sup>d</sup>	Chloromethyl methyl ether <sup>e</sup>	2-Ethoxyethyl acetate	Methoxy-1,3,5,7-cyclooctatetraene
Benzyl ethyl ether <sup>d</sup>	$\beta$ -Chlorophenetole	(2-Ethoxyethyl)- <i>o</i> -benzoyl benzoate	$\beta$ -Methoxypropionitrile
Benzyl methyl ether	<i>o</i> -Chlorophenetole	1-Ethoxynaphthalene	<i>m</i> -Nitrophenetole
Benzyl 1-naphthyl ether <sup>d</sup>	<i>p</i> -Chlorophenetole	<i>o,p</i> -Ethoxyphenyl isocyanate	1-Octene
1,2-Bis(2-chloroethoxy)ethane	Cyclooctene <sup>d</sup>	1-Ethoxy-2-propyne	Oxybis(2-ethyl acetate)
Bis(2 ethoxyethyl) ether	Cyclopropyl methyl ether	3-Ethoxypropionitrile	Oxybis(2-ethyl benzoate)
Bis(2-(methoxyethoxy)ethyl) ether	Diallyl ether <sup>d</sup>	2-Ethylacrylaldehyde oxime	$\beta,\beta$ -Oxydipropionitrile
Bis(2-chloroethyl) ether	<i>p</i> -Di- <i>n</i> -butoxybenzene	2-Ethylbutanol	1-Pentene
Bis(2-ethoxyethyl) adipate	1,2-Dibenzoyloxyethane <sup>d</sup>	Ethyl $\beta$ -ethoxypropionate	Phenoxyacetyl chloride
Bis(2-ethoxyethyl) phthalate	<i>p</i> -Dibenzoyloxybenzene <sup>d</sup>	2-Ethylhexanal	$\alpha$ -Phenoxypropionyl chloride
Bis(2-methoxyethyl) carbonate	1,2-Dichloroethyl ethyl ether	Ethyl vinyl ether	Phenyl <i>o</i> -propyl ether
Bis(2-methoxyethyl) ether	2,4-Dichlorophenetole	Furan	<i>p</i> -Phenylphenetone
Bis(2-methoxyethyl) phthalate	Diethoxymethane <sup>d</sup>	2,5-Hexadiyn-1-ol	<i>n</i> -Propyl ether
Bis(2-methoxymethyl) adipate	2,2-Diethoxypropane	4,5-Hexadien-2-yn-1-ol	<i>n</i> -Propyl isopropyl ether
Bis(2- <i>n</i> -butoxyethyl) phthalate	Diethyl ethoxymethylenemalonate	<i>n</i> -Hexyl ether	Sodium 8,11,14-eicosatetraenoate
Bis(2-phenoxyethyl) ether	Diethyl fumarate <sup>d</sup>	<i>o,p</i> -Iodophenetole	Sodium ethoxyacetylde <sup>d</sup>
Bis(4-chlorobutyl) ether	Diethyl acetal <sup>d</sup>	Isoamyl benzyl ether <sup>d</sup>	Tetrahydropyran
Bis(chloromethyl) ether <sup>e</sup>	Diethylketene <sup>f</sup>	Isoamyl ether <sup>d</sup>	Triethylene glycol diacetate
2-Bromomethyl ethyl ether	<i>m,o,p</i> -Diethoxybenzene	Isobutyl vinyl ether	Triethylene glycol dipropionate
$\beta$ -Bromophenetole	1,2-Diethoxyethane	Isophorone <sup>d</sup>	1,3,3-Trimethoxypropene <sup>d</sup>
<i>o</i> -Bromophenetole	Dimethoxymethane <sup>d</sup>	$\beta$ -Isopropoxypropionitrile <sup>d</sup>	1,1,2,3-Tetrachloro-1,3-butadiene
<i>p</i> -Bromophenetole	1,1-Dimethoxyethane <sup>d</sup>	Isopropyl 2,4,5-trichlorophenoxyacetate	4-Vinyl cyclohexene
3-Bromopropyl phenyl ether	Dimethylketene <sup>f</sup>	Limonene	Vinylene carbonate
1,3-Butadiyne	3,3-Dimethoxypropene	1,5- <i>p</i> -Methadiene	Vinylidene chloride <sup>d</sup>
Buten-3-yne	2,4-Dinitrophenetole	Methyl <i>p</i> -( <i>n</i> -amyloxy)benzoate	
<i>tert</i> -Butyl ethyl ether	1,3-Dioxepane <sup>d</sup>		

**Notes**

<sup>a</sup> When stored as a liquid monomer.

<sup>b</sup> Although these chemicals form peroxides, no explosions involving these monomers have been reported.

<sup>c</sup> When stored in liquid form, these chemicals form explosive levels of peroxides without concentration. They may also be stored as a gas in gas cylinders. When stored as a gas, these chemicals may autopolymerize as a result of peroxide accumulation.

<sup>d</sup> These chemicals easily form peroxides and should probably be considered under Part B.

<sup>e</sup> OSHA-regulated carcinogen.

<sup>f</sup> Extremely reactive and unstable compound.

**Source:** References 2 and 3.

In most peroxide safety programs, a concentration of 100 ppm of peroxides is used as a control point. However, this value has no scientific justification. This criterion seems to be based on the practical limit of detection of the potassium iodide method traditionally used to detect peroxides. It is likely that this value is at least 1 order of magnitude overly conservative in some cases.

Notably, this value is almost certainly quite overly conservative and excessively burdensome for the chemicals shown in Part B of Table 1 when they are not used in distillations or other similar processes. For example, it certainly seems excessive to limit the amount of peroxide in isopropanol used as a wipe cleaning compound to 100 ppm.

From a theoretical perspective, it should be impossible for most solutions of <1% peroxides to explode. However, the

selection of a rational peroxide concentration control value is complicated by several factors. For example, when peroxidized chemicals are dispensed from screw-cap bottles, some of the liquid may remain on the threads and cap. The liquid evaporates, leaving pure peroxide in the threads of the cap. Unscrewing the cap may initiate an explosion (16, 17). Thus, a solvent with modest peroxide contamination can explode because of peroxide concentration at the cap.

Dilute solutions of peroxidizable chemicals do not usually pose a peroxide hazard. For example, solutions of polyether nonionic surfactants usually are adequately dilute to prohibit the formation of dangerous concentrations of peroxides. Furthermore, they have a low volatility (boiling point above 300 °C or a vapor pressure of <0.1 mm Hg at 20 °C) and are not likely to concentrate. In most cases, dilute solutions of

low-volatility peroxidizables need not be treated as peroxidizables (2, 3).

### Inhibitors

Many methods can be used to stabilize or inhibit peroxidizable organic chemicals and thus reduce oxidation. Use and storage under an inert atmosphere are helpful precautions and will greatly reduce peroxidation in most cases. Some manufacturers add hydroquinone, 2,6-di-*tert*-butyl-*p*-methylphenol (BHT), diphenylamine, or a similar compound to the chemical in trace quantities. Phenolic compounds are often added to commercial vinyl monomers. It is interesting that phenolic inhibitors are ineffective if some oxygen is not present; thus, these inhibited chemicals should not be stored under inert gas (2).

Iron will inhibit the formation of peroxides in diethyl ether, which is one reason that this compound is usually sold in steel containers. However, iron or other metals will not inhibit isopropyl ether and are not known to be effective for other chemicals. In fact, iron may catalyze peroxidation in some chemicals. Despite the use of inhibitors, peroxide explosions have occurred. Inhibitors are only one part of a peroxide control program.

Inhibitors are depleted as peroxides are formed and degraded. Eventually, the inhibitor is totally depleted, and the peroxide-forming chemical will act as an uninhibited chemical. This may result in the rapid accumulation of peroxides in a chemical that has been stable for a long time. If inhibited chemicals are retained for extended periods, not only must the peroxide content be periodically evaluated, but the inhibitor level should be determined (3). If the inhibitor is exhausted, new inhibitor must be added or the chemical must be treated as an uninhibited chemical.

### Control of peroxidizable organic chemicals

The control program set forth here represents common practice and generally accepted procedures. As noted above, some of these requirements may be excessively restrictive, reflecting the lack of a sound scientific basis. On the other hand, following these guidelines is no guarantee that an explosion will never occur.

**Purchasing and storage.** Ideally, purchases of peroxidizable chemicals should be restricted to ensure that the chemical is used completely before it can become peroxidized. Table 2 shows some commonly recommended safe storage periods for peroxide formers (2, 3). It should be stressed that these are minimum criteria, and many authors suggest more frequent testing. In the past, the National Research Council recommended testing of chemicals in Part B of Table 1 every 6 months (18), but it makes no specific recommendation in its most recent publication (6). The ACS Committee on Chemical Safety recommends a blanket 3-month time limit for all peroxidizables unless tested and found to be peroxide free (19). The University of California at Davis places a 12-month limit on the storage of unopened containers and stipulates a maximum storage time of 3–6 months for opened containers (14). Baumgarten (20) recommends that containers of uninhibited THF not be used for distillation 2–3 days after opening. The chemist or industrial hygienist should be alert for operations and uses of peroxidizable chemicals in

**Table 2. Safe storage period for peroxide formers<sup>a</sup>**

Description	Period
Unopened chemicals from manufacturer	18 months
Opened containers	
Chemicals in Part A, Table 1	3 months
Chemicals in Parts B and D, Table 1	12 months
Uninhibited chemicals in Part C, Table 1	24 hours
Inhibited chemicals in Part C, Table 1	12 months <sup>b</sup>

**Notes**  
<sup>a</sup> Data from References 2 and 3.  
<sup>b</sup> Do not store under inert atmosphere.

which more frequent testing should be recommended, such as chemicals in frequent use or prolonged storage, use involving extensive evaporation or air exposure or light or heat exposure, and use in distillation without substantial bottoms.

Containers of peroxidizable chemicals must be dated when received and again when opened. Many commercially purchased ethers have a manufacturer's bottling date and expiration date. However, because many manufacturers do not put expiration dates on containers of other types of peroxide formers, the organization or person receiving the chemical must provide a receipt date. The person who opens the container should add an opening date. Figure 2 shows the label used at the Lawrence Livermore National Laboratory.

All peroxide formers should be stored in sealed, air-impermeable containers. In most cases, dark amber glass with a tight-fitting cap is appropriate. Diethyl ether should be stored in steel containers because the iron tends to neutralize peroxides. At least one manufacturer is now providing 2-propanol in steel containers. Containers with loose-fitting lids and ground glass stoppers on glass bottles should not be used for storage. Generally, plastic containers should not be used, although an exception is often made for relatively short-term storage of 2-propanol in plastic squeeze bottles smaller than 1 L. Experience has shown that such storage does not result in hazardous peroxide accumulation under normal use. However, 2-propanol that will be distilled should not be stored in plastic bottles. Chemicals that are listed in Part A of Table 1 should be stored under nitrogen if possible.

**Surveillance.** A responsible person should maintain an inventory of peroxidizable chemicals or annotate a general chemical inventory to indicate which chemicals are subject to peroxidation. By the expiration date, the person using the chemical or the person responsible for the chemical should either dispose of the chemical or test it for peroxide content using one of the procedures described below. Any chemical with a peroxide content  $\geq 100$  ppm should be disposed of or decontaminated.

Chemicals inhibited with low levels of antioxidants should be tested for antioxidant capacity (inhibitor level or function) if peroxide concentrations  $> 25$  ppm are detected during any test. If the inhibitor is exhausted, a new inhibitor of the type and concentration originally used by the manufacturer should be added, or the chemical should be treated as if it is uninhibited.

## **WARNING: MAY FORM EXPLOSIVE PEROXIDES**

Store in tightly closed original container. Avoid exposure to light, air, and heat. If crystals, discoloration, or layering are visible, contact your ES&H Team immediately. Check for peroxides before distilling or concentrating.

### **THIS CHEMICAL HAS A LIMITED SHELF LIFE**

Container received on \_\_\_\_\_ . Container opened on \_\_\_\_\_ .

Test or dispose of \_\_\_\_\_ months after receipt or \_\_\_\_\_ months after opening.  
Do not use chemical if >100 ppm of peroxides are detected.

### **TESTING, DEPEROXIDATION, AND STABILIZATION RECORD**

Test Date \_\_\_\_\_ Peroxides \_\_\_\_\_ Post-Treatment \_\_\_\_\_ Inhibitor Added \_\_\_\_\_

Test Date \_\_\_\_\_ Peroxides \_\_\_\_\_ Post-Treatment \_\_\_\_\_ Inhibitor Added \_\_\_\_\_

**Figure 2.** Label for peroxide-forming chemicals.

Old containers of peroxidizable chemicals, or containers of unknown age or history, must be handled very carefully. Any peroxidizable chemical with visible discoloration, crystallization, or liquid stratification should be treated as potentially explosive. If the container shows no outward sign of deterioration, it may be possible to test the chemical by using special precautions against agitation and providing extra protection to the tester. Typically, the unopened container should be carried to a nearby hood by a person wearing chemical goggles, a face shield, heavy gloves, ear muffs, and a thick wool or tough quilted cloth overgarment covering the body, arms, and legs from the chin to the wrists and ankles. A heavy rubber apron should be worn over the other protective clothing. In the hood, with secondary containment and using a blast shield, the person should test the chemical with the least possible disturbance, typically by use of a colorimetric peroxide test strip. If high levels of peroxide are detected, the container should be handled as a potential bomb.

**Use.** Operations that result in evaporation of peroxide formers or extensive exposure to air or oxygen are particularly dangerous. Distillation is notable for the number of accidents it has caused. Any peroxide former that is to be distilled should be tested for peroxides before use—preferably immediately before use. The chemical should not be distilled if it contains >100 ppm of peroxides. Any distillation operation using peroxide formers should leave at least 10% bottoms, and 20% bottoms should be used until it is determined that the operation does not accumulate explosive levels of peroxides. If possible, add a nonvolatile organic compound such as mineral oil to the distillation. It will remain behind and dilute the remaining peroxides. During distillation, the solution must be stirred with a magnetic stirrer or an inert gas bleed. Air or other oxygen-containing mixtures should never be used to maintain mixing during distillation.

The peroxides in higher boiling point chemicals are usually degraded during distillation. Long-chain alkyl ethers and the glycol ethers are such chemicals. However, if they are distilled at reduced pressure, reducing the temperature of the process, decomposition may not occur and unstable levels of peroxide concentrations may result. Uninhibited chemicals in Part C of Table 1 should not be distilled.

#### **Peroxide detection methods**

Although there are numerous quantitative, semiquantitative, and qualitative methods to detect peroxides in organic and aqueous solutions, four are commonly used. They include two qualitative variations on the iodine detection method, the qualitative ferrous thiocyanate method, and the use of semiquantitative redox dip strips. Recently, the use of titanium sulfate has been suggested as a means to detect peroxides (21), but it is not widely used.

The dip strip method has the advantage of being the most gentle test, an important consideration if the chemical is shock sensitive. It also has another substantial advantage: It can detect, to some extent, dialkyl peroxides, polyperoxides, and cyclic peroxides, compounds that are not efficiently detected by the other methods (except, perhaps, the titanium sulfate method). Some solvents, notably isopropyl ether and dioxane, may form significant and hazardous levels of these higher reaction products. Furthermore, the standard peroxide removal procedures may remove all of the hydroperoxides but leave behind dangerous levels of alkyl peroxides, polyperoxides, and cyclic peroxides (1, 11). The routine ferrous thiocyanate and iodine methods may yield a false negative in this case, but the dip strip test would likely detect the remaining peroxides, although perhaps not quantitatively. The dip strip method, however, is difficult to use with water-immiscible, low-volatility chemicals.

Additional tests include the perchromate test and the mercury test. A comparatively complex reflux method is available for the detection of total peroxides, including alkyl peroxides and polyperoxides (4, 22).

**Ferrous thiocyanate method** (2, 3). This qualitative method relies on the oxidation by peroxide of colorless ferrous thiocyanate ( $\text{Fe}^{2+}$ ) to the red ferrithiocyanate ( $\text{Fe}^{3+}$ ). One drop of reagent is added to one drop of the chemical to be tested. A barely discernible pink color indicates that peroxides are present at a concentration of about 10 ppm. A clear pink to cherry color suggests a concentration of about 20 ppm. A red color indicates a concentration of about 80 ppm, and a deep red indicates a concentration as high as 400 ppm.

The reagent is prepared by dissolving 9 g  $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$  in 50 mL 18% HCl. A little granulated zinc is added, followed by 5 g NaSCN. When the transient red color fades, an additional 12 g NaSCN is added, and the liquid is decanted from the unused zinc into a clean, stoppered bottle. The shelf life of this reagent is very limited.

This method is sensitive only to hydroperoxides; it will not detect most other peroxides. However, this method is very sensitive and rapid for the detection of hydroperoxides, and a quantitative photometric version of this test has been developed (23).

**Iodide tests.** This is the most common qualitative test for adventitious peroxides. The two primary variations on this procedure involve the oxidation of iodide to iodine by the peroxide, with the resulting formation of a yellow to brown color. ASTM has published a version of this method (24), and commercial test kits using this principle are available from many sources.

**Method A.** In this method, 1 mL of the material to be tested is added to an equal volume of glacial acetic acid, to which approximately 0.1 g NaI or KI (10% wt/vol) has been added. A yellow color indicates a low concentration of peroxides (40–100 ppm as hydrogen peroxide). A brown color indicates a higher concentration of peroxide. Blanks must always be prepared. The test solution has a very short shelf life and will naturally result in high blank values if stored for any length of time. Variations on this method include the use of a 20% wt/vol reagent and hydrochloric acid instead of glacial acetic acid (11) and the use of sulfuric acid (13). Heating is recommended to enhance detection of higher peroxides that may not be detected by the routine process (4).

In quantitative variations on this method, the liberated iodine is titrated with 0.1 M NaSCN (4). This degree of precision is usually unnecessary for routine testing, and these methods do not increase the sensitivity of the method to higher peroxides.

**Method B.** In this method, 1 mL of a freshly prepared 10% KI solution is added to 10 mL of the organic liquid in a 25-mL glass stoppered vial. A barely visible yellow color suggests a peroxide content of 10–50 ppm. A clear and definite yellow color indicates a concentration of about 100 ppm, and a brown color indicates a higher concentration. Variations on this method include using a 20% KI solution and using a 1:1 solvent/reagent ratio (8). Some authors recommend vigorous shaking or mixing.

**Comparison of Methods A and B.** Method A is often faster than Method B. Up to 15 min may be required for formation

of color in Method B, whereas the color usually forms in <1 min for Method A (2, 3). For both procedures, the color formed is a function of the peroxide content and the chemical tested.

Some scientists disagree about the sensitivity of these methods to peroxides other than hydroperoxides. Burfield (11) states that the method is sensitive only to hydroperoxides. Noller and Bolton (4) indicate that the acidified Method A is sensitive to hydroperoxides, peroxyacids, diacyl peroxides, and some peroxide esters, but not to dialkyl and alkylidene peroxides. Davies (1) makes a similar statement. Noller and Bolton (4) suggest that heating, perhaps with the addition of hydroiodic acid, may be necessary to detect these compounds. Mair and Graupner (22) use a combination of glacial acetic acid and hydrochloric acid plus heat to detect all peroxides. These latter two procedures are complex reflux processes that require extensive experience in chemistry and substantial lab facilities.

**Dip strips.** E. Merck and Aldrich Chemical make dip strips for the semiquantitative detection of peroxides in organic and inorganic solutions, and they are available from many suppliers. The strip incorporates the enzyme peroxidase, which transfers oxygen from peroxide to an incorporated organic redox indicator. The indicator turns blue in the presence of peroxides. Comparison color scales are provided for organic and aqueous tests. The range for organic chemicals varies, depending on the manufacturer: 0–25 ppm for the Merck product and 1–100 ppm for Aldrich. Higher ranges can be accommodated by dilution of the suspect chemical with a miscible, nonperoxidized chemical.

For volatile organic chemicals, the test strip is immersed in the chemical for 1 s; then the tester breathes slowly on the test strip for 15–30 s, or until the color stabilizes. Vapor in the breath provides water for the reaction to proceed. The color is then compared with the scale provided on the bottle.

Modifications of this procedure are needed to test non-volatile organic compounds. The Aldrich strips have been successfully used as follows (8). For water-miscible compounds, add three drops of water to one drop of chemical to be tested. Wet the dip strip in the mixture, wait 2–3 min or until the color stabilizes, and multiply the result by 4. For water-immiscible compounds, mix three drops of a volatile ether with one drop of the low-volatility compound to be tested. Wet the dip strip and breathe on the reaction zone for 30–60 s, or until the color stabilizes, and multiply the measured value by 4.

Bottles of 100 strips cost about \$45. The article by Mirafzal and Baumgarten (8) compared the test strips (Aldrich version) with traditional methods and found good agreement. These strips have a limited shelf life, but refrigeration is not recommended once the container has been opened, because repeated cooling and heating cause condensation that will ruin the strips. Storage under a dry, inert atmosphere will prolong the shelf life.

Literature from E. Merck indicates that their test strips will detect hydroperoxides and most higher peroxides, but some polyperoxides may be poorly detected (25).

**Titanium sulfate.** Historically, the reaction between titanium and peroxide has been used for the detection of titanium (26) and the detection of organic and inorganic perox-

ides (27, 28). To detect organic peroxides, a solution of titanium sulfate in 50% sulfuric acid is used. When this reagent is added to a peroxidized solvent, a yellow-orange complex is formed. It has been stated that this method will detect higher peroxides, especially polyperoxides (21, 29). The higher peroxides are hydrolyzed by the strong acid and are thereby made detectable.

The test reagent is prepared by dissolving a small amount of  $\text{TiO}_2$  in hot concentrated sulfuric acid and adding this to an equal volume of water. Although it is a very old procedure, there is not a lot of modern experience or literature that discusses this method in any detail. Little seems to be readily available on the limit of detection of the method, stability of the reagent, specific procedures for its use, or the sensitivity to higher peroxides other than polyperoxides. As discussed previously, strongly acidified versions of more traditional methods have been outlined (4, 22), and it is unclear what advantage the titanium sulfate procedure has relative to these procedures. This method can only be recommended if it is compared by the user with other methods of known sensitivity and used accordingly.

**Summary of detection methods.** Dip strips provide the highest sensitivity and the most accurate quantitation of peroxide concentrations for routine testing. Furthermore, they are easier, faster, and safer to use than other methods, and they detect a wider range of peroxides than do other simple methods. They are, however, somewhat inconvenient to use when testing nonvolatile solvents, and they have a limited shelf life after the container is opened.

If it is important to detect all peroxides, including alkyl peroxides and polyperoxides, the acid reflux method should be used by a knowledgeable chemist in a laboratory hood. The titanium sulfate method may prove to be equivalent, but supporting data on this procedure are limited. Where precision is desired, the quantitative versions of the potassium iodide or ferrous thiocyanide tests may be used. If absolute precision and accuracy are required, the potassium iodide-acid reflux combination method should be considered.

### Removal of peroxides

In some cases, it might be desirable to remove peroxides from chemicals rather than dispose of the entire chemical. This can be done safely for relatively low levels of peroxides (<500–1000 ppm). Scrubbing of concentrations >1000 ppm may pose an unacceptable hazard, depending on the chemical involved. Scrubbing of discolored, crystallized, or layered peroxide formers is almost certainly too hazardous and should not be attempted. These severely peroxidized compounds should be treated as potential bombs.

Many methods and materials have been used to remove peroxides: activated alumina, ferrous salts, assorted amines, sodium metabisulfate, potassium permanganate, silver hydroxide, stannous chloride, sodium hydroxide, cerous hydroxide, sodium, lithium, lithium aluminum hydride, sodium perborate, hydroquinone, ion-exchange resins, copper chloride, indicating molecular sieves, triphenylphosphene, lead oxide, acidified zinc, iron, mercury, sodium carbonate, ammonia, glacial acetic acid, and phosphoric acid esters.

All methods have some drawbacks. Some are potentially explosive, such as those involving the use of alkali metals,

alkali metal hydrides, sodium borohydride, sodium hydroxide, and reflux over cuprous chloride or stannous chloride. Some methods entail heating, refluxing, or other operations that require special expertise and equipment. These include refluxing with indicating activated molecular sieves; refluxing with hydrochloric acid, potassium iodide, and acetic acid; and refluxing with cuprous chloride or stannous chloride. Some methods, such as the use of mercury, ion-exchange resins and molecular sieves, generate undesirable waste products. Others, including the use of ferrous sulfate or sodium bisulfite solutions, tend to introduce water into the solvent, which may need to be removed. Finally, many methods, such as the use of indicating molecular sieves, cuprous chloride, and ferrous sulfate, fail to remove dialkyl or higher peroxides.

**Method 1 (2).** Hydroperoxides can be removed by passing the solvent through a column of activated alumina. This method works for water-soluble and water-insoluble chemicals. The washed solvent should be retested to ensure that it has been cleaned adequately. The alumina apparently catalyzes the degradation of some peroxides, but in some cases the peroxide may remain intact on the alumina, making it potentially shock sensitive. The alumina can be deactivated by flushing with a dilute acid solution of potassium iodide or ferrous sulfate.

The amount of alumina required depends on the quantity of peroxide. As a start, a column containing 100 g of alumina should be used for 100 mL of solvent (8). More alumina or passage through a second column may be required to eliminate peroxides. This method is relatively slow and expensive, but it avoids shaking the solvent and does not add water. It will not reliably remove dialkyl peroxides, although there is some controversy about this (1).

**Method 2 (2).** Peroxides in water-insoluble chemicals can be removed by shaking with a concentrated solution of ferrous salt; 60 g  $\text{FeSO}_4$ , 6 mL concentrated  $\text{H}_2\text{SO}_4$ , and 110 mL  $\text{H}_2\text{O}$  are a standard solution. Another formulation is 100 g  $\text{FeSO}_4$ , 42 mL concentrated HCl, and 85 mL  $\text{H}_2\text{O}$ . The peroxide former is extracted two to three times with an equal volume of the reagent. Drying over sodium or magnesium sulfate can be used to remove dissolved water. Shaking should be very gentle for the first extraction. This method has been shown repeatedly to be quite effective for most peroxides, but it is not reliable for removing alkyl peroxides.

**Method 3 (11).** Blue-indicating molecular sieve (4–8 mesh, type 4A) is added to containers of peroxidized chemicals and allowed to sit for 1–30 days. An amount equivalent to about 5–10% (wt/vol) of the peroxidized liquid is used. Alternatively, the mixture can be refluxed, and the reaction occurs within 4 h. The peroxide is broken down, and the indicator in the sieve is consumed. When run at room temperature, this process is apparently safe, slow, and controlled. Dialkyl peroxides are not efficiently removed, especially from dioxane. This method may be particularly suited to treatment of THF, diisopropyl ethers, and diethyl ethers, which may be decontaminated at room temperature in a couple of days.

**Other methods of removing higher peroxides, including dialkyl peroxides.** In one suggested procedure, a 10% molar excess of sodium or potassium iodide is dissolved in 70 mL



glacial acetic acid. A small quantity of 36% (wt/vol) HCl is added, followed by 0.01 mol of the dialkyl peroxide. The solution is heated to 90–100 °C on a steam bath over the course of 30 min and held at that temperature for 5 h (6). Zinc dissolved in acetic or hydrochloric acid has been recommended (1, 4). Prolonged treatment with ferrous sulfate in 50% sulfuric acid has also been recommended (1).

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