

Peroxide Forming Compounds

Peroxide formation in laboratory solutions and reagents by auto-oxidation has caused many laboratory accidents, including unexpected explosions of residues remaining after solvent distillation. Many liquid, a few solid and a few gaseous organic and a few inorganic solid compounds form peroxides over time. Peroxides form by the reaction of the chemical with oxygen allowed in the headspace of chemical containers once the container is opened for the first time. Most organic peroxides are sensitive, to varying degrees, to shock, heat or friction.

The rate of peroxide formation will depend upon the compound. Some peroxides quickly build up to an explosive level and some are only explosive on concentration, such as when a solvent is distilled. Peroxidizable compounds contain a reactive hydrogen atom that is 'activated' by adjacent structural components. The dangers of peroxide formation can be divided into three groups (Attachment, Tables A-C). In addition, there are a number of chemical compounds that may form peroxides, but do not clearly fit into categories A-C. (These are listed in the Attachment in Table D.)

Although there is no agreement upon what level of peroxides present a significant hazard, several sources suggest that the "safe" range of peroxide formation is 100 ppm or less. Therefore it is DRI policy that all peroxide forming chemicals be tested at the end of the appropriate storage period. If peroxides are detected at a level above 100 ppm, the material must be decontaminated with standard procedures for deperoxidation or discarded as hazardous waste. Test strips for the detection of peroxides may be purchased from various safety-supply vendors, including Lab Safety Supply, VWR and Fisher Scientific. Several chemical methods for the detection of peroxides are also available in the published literature.

Control and Safe Use of Peroxide Formers

Peroxide formation may be controlled by the following methods:

- Date all incoming containers of peroxide formers when received and again when opened. Many chemical companies now routinely print an expiration date on containers of the worst peroxide formers.
- Purchase the smallest possible container size for your needs. Inhibitors are added to some chemicals and the purchase of peroxide formers with added inhibitors is encouraged. However, be aware, that these free radical inhibitors will be depleted over time as peroxides are formed. Additionally distillation removes the inhibitor. Distilled peroxide formers and those retained for extended periods should be checked for inhibitor concentration and inhibitor added if below the manufacturer's recommended concentration.
- Store peroxide formers in sealed, air-impermeable containers such as dark amber glass with a tight-fitting cap. Iron inhibits the formation of peroxides in some materials, which is why diethyl ether and some other materials are sold in metal cans. Ground glass stoppered bottles and plastic containers are not advisable, however, plastic squeeze bottles may be used for small quantities of some materials, such as 2-propanol, for immediate use.
- Containers of peroxide formers should be stored away from heat and light and protected from physical damage and ignition sources.

- Peroxide forming compounds should not be stored at or lower than the temperature at which the peroxide freezes or precipitates, as this will make these compounds extremely sensitive to shock. Note: refrigeration does not prevent (and may not inhibit) peroxide formation.
- Store peroxide formers, especially those listed in Table A, under nitrogen or other inert gas or keep and use them in an inert atmosphere chamber. Note: Some inhibitors actually need small amounts of oxygen to prevent peroxide formation, therefore it is recommended that inhibited chemicals are not stored under an inert atmosphere.
- Avoid the distillation of peroxide formers without first testing for the existence of peroxides. Most explosions occur when a material is distilled to dryness. Leave at least 10-20% in still bottom. Stir such distillations with a mechanical stirrer or an inert gas. (Air or an oxygen containing mixture should never be used for this purpose.)
- Do not evaporate containers that held peroxide forming compounds to dryness for reuse unless it is known that the chemical was peroxide-free.
- Inspect containers of peroxide forming chemicals frequently, looking for signs of precipitation, stratification of liquid, crystal formation or other irregularities. Note: the presence of any of these signs indicates the potential for a shock sensitive container. **Do not move the container and contact EH&S as soon as possible.**
- After each use, carefully wipe the container neck, cap and threads with a cloth before resealing.

Safe Storage Periods for Peroxide Formers

Unopened chemicals from manufacturer:	18 months
Opened containers:	
Chemicals in Table A.	3 months
Chemicals in Tables B. and D.	12 months
Uninhibited chemicals in Table C.	24 hours
Inhibited chemicals in Table C. (Do not store under an inert atmosphere)	12 months

Evaluation of Peroxide-Forming Chemicals

Safety Precautions: Personnel handling containers of outdated peroxide-forming chemicals must wear chemical goggles and a face shield, heavy gloves, and a buttoned lab coat. Hearing protection (plugs or muffs) and a rubber apron are also recommended. Suspect chemical containers must be transferred, one at a time, to a clean (no other chemicals) lab hood. A blast shield must be used when opening or manipulating containers, and testing peroxide levels. Never attempt to force open a stuck cap on a container. Secondary containment for the chemical should also be utilized if practical. Tongs or other forms of remote handling should be used as much as practical. Verify that an operable safety shower/eyewash and fire extinguisher is readily accessible. At least one other person not directly involved in handling of the chemicals should be present.

Peroxide-forming liquid chemicals which have not been tested for peroxides within the time periods listed in the table above must be evaluated as follows:

1. *Visual Inspection*

Visually inspect all peroxide-forming chemicals before any further evaluation. Containers that exhibit any unusual visual characteristics, such as the examples listed below, should be assumed to contain dangerous levels of peroxides and should not be disturbed. Notify EH&S, who will assist in the further evaluation. If there is any doubt about the safety of handling a chemical container, notify EH&S immediately.

Liquid Chemicals

- Crystallization (around the cap or in the liquid)
- Visible discoloration
- Liquid stratification

Note: A flashlight or other light source can be used to increase the visibility of the interior of amber bottles.

Diethyl ether is commonly sold in steel containers which prevents visual inspection of the liquid. Therefore, diethyl ether containers whose age and use history are unknown should be assumed to contain dangerous levels of peroxides and should not be disturbed.

Solid Chemicals (potassium metal, potassium and sodium amide)

- Discoloration and/or formation of a surface crust (for example, potassium metal forms a yellow or orange superoxide at the surface)

Note: Evaluation of alkali metals and their amides is based on visual criteria only. These substances react strongly with water and oxygen, and standard peroxide tests should not be used.

Materials meeting the above criteria are considered to be high risk and will have to be disposed of by special means (limit handling and movement; notify EH&S). Only chemicals that pass visual inspection should be evaluated further.

2. *Opening Container* (Note: Never try to force open a rusted or stuck cap on a container of a peroxide-forming chemical.)

- a. Only chemicals that meet the below criteria should be opened and tested for peroxides. Chemicals that do not meet one or more of these criteria should be considered to be high risk, and should not be disturbed. Limit handling and movement; notify EH&S.
 - The identity of the chemical is known.
 - The age of the chemical (since manufacture) is known.

- Evaporation of the chemical is thought to be less than 10% - if this is in question, assume that evaporation has occurred and that high peroxide levels may be present.

b. Additionally, the following classification-specific criteria must be met:

List A Chemicals

- Previously opened chemicals not used in the preceding 3 months must be less than 6 months old.
- Chemicals unopened from the manufacturer must be less than 2 years old. If this is in question, assume the container has been opened.

List B and List C (liquids) Chemicals

- Opened chemicals not used in the preceding 12 months must be less than 5 years old.
- Chemicals unopened from the manufacturer must be less than 10 years old. If this is in question, assume the container has been opened.

Chemicals not meeting the minimum criteria for opening and testing will be considered to be high risk and must be disposed of by special means. Limit handling and movement; notify EH&S.

If after opening the container, visual irregularities such as those listed in section 1 are apparent, assume that dangerous levels of peroxides are present. Gently cover the container to minimize evaporation, limit handling and movement, and notify EH&S as soon as possible.

3. *Peroxide testing*

For chemicals that have been determined to be safe to open, measure the peroxide concentration using commercial peroxide test strips. Wet chemical detection methods are also available; however, the test strips are gentler, easier, faster, and have greater sensitivity and accuracy, and therefore are recommended for most applications. Laboratory personnel are responsible for performing peroxide testing of peroxide forming chemicals present in their laboratories or storage areas. EM Quant Peroxide test strips manufactured by EM Science (E. Merck) are available from many suppliers (such as Fisher Scientific, Lab Safety and VWR). Chemicals that contain peroxide levels that exceed the test strip detection range may be diluted with a miscible, peroxide-free, solvent and retested.

Disposal of peroxide forming chemicals

1. Chemicals with a peroxide concentration of less than 30 ppm can be disposed of through EH&S. Laboratory personnel are responsible for decontaminating chemicals that contain greater than 30 ppm peroxides prior to disposal.

2. Chemicals with a peroxide concentration greater than 800 ppm are considered high risk, and require disposal by special means. DO NOT attempt to decrease peroxide concentration. Limit handling and movement of the chemical container. Notify EH&S.
3. Peroxide forming chemicals with a peroxide concentration greater than 100 ppm must be disposed of. (Exception: a container of a chemical on list B with a peroxide concentration of less than 800 ppm, can be decontaminated and maintained for future use upon the approval of the responsible principal investigator or laboratory supervisor).
4. Chemicals with a peroxide concentration less than 800 ppm must be decontaminated to reduce the peroxide concentration to less than 30 ppm before disposal. Peroxides can be removed by chemical treatment or column separation (1, 2). Verify treatment with testing. Notify EH&S of treatment and subsequent peroxide concentration when submitting request for waste removal.

Preparation of Peroxide Formers for Disposal

Water-insoluble peroxide formers (ethers, hydrocarbons, etc.) can be decontaminated by shaking with a concentrated ferrous salt solution (5). A solution of 6 g of ferrous sulfate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$), 6 ml of concentrated sulfuric acid, and 11 ml of water is mixed with 1 L of the peroxide former until the peroxide concentration is reduced to below 30 ppm. Reduction of the peroxides generally takes only a few minutes. Re-test the peroxide former after decontamination to verify that the peroxide concentration is less than 30 ppm. Dispose of the decontaminated peroxide former as soon as possible through EH&S (report final peroxide concentration). An alumina column is used as the standard procedure to decontaminate water-soluble peroxide formers (1, 2). Contact EH&S for guidance on decontamination of these chemicals.

In some instances it may be permissible to dilute the peroxide concentration to below 30 ppm by mixing the peroxide former with a chemically compatible chemical waste stream or chemical solvent. Contact EH&S prior to diluting any peroxide former in preparation for disposal. After diluting the peroxide former, verify that the peroxide concentration of the resulting mixture is less than 30 ppm, and then dispose of the waste mixture through EH&S (report final peroxide concentration).

References

1. Kelly, R. J., "Review of Safety Guidelines for Peroxidizable Organic Chemicals", *Chem. Health Saf.* **1996**, 3(5), 28-36
2. Jackson, H. L.; McCormack, W. B.; Rondestvedt, C. S.; Smeltz, K. C.; Viele, I. E. *J. Chem. Educ.* **1970**, 47(3), A175-88
3. Clark, D. E., "Peroxides and Peroxide Forming Compounds", *Chem. Health Saf.* **2001**, 8(5), 12-21
4. National Safety Council, Recognition and Handling of Peroxidizable Compounds, **1987**, Data Sheet I-655-Rev. 87
5. National Research Council, *Prudent Practices in the Laboratory: Handling and Disposal of Chemicals*; National Academy Press: Washington, D. C., **1995**; pp. 162-163.
6. Kelley, R. J., "Peroxidizable Organic Chemicals", Handbook of Chemical Health and Safety, Chapter 52, ACS, **2001**

Attachment—Tables of Peroxide Forming Compounds

Table A--Chemicals that form explosive levels of peroxides without concentration.

Butadiene ^a	Isopropyl ether	Sodium amide (sodamide)
Chloroprene ^a	Potassium amide	Tetrafluoroethylene ^a
Divinylacetylene	Potassium metal	Vinylidene chloride

Table B--Chemicals that form explosive levels of peroxides upon concentration

Acetal	Diethyl ether	2-Pentanol
Acetaldehyde	Diethylene glycol dimethyl ether (diglyme)	4-Penten-1-ol
Benzyl alcohol	Dioxanes	1-Phenylethanol
2-Butanol	Ethylene glycol dimethyl ether (glyme)	2-Phenylethanol
Cumene	4-Heptanol	2-Propanol
Cyclohexanol	2-Hexanol	Tetrahydrofuran
2-Cyclohexen-1-ol	Methylacetylene	Tetrahydronaphthalene
Cyclohexene	3-Methyl-1-butanol	Vinyl ethers
Decahydronaphthalene	Methylcyclopentane	Other secondary alcohols
Diacetylene	Methyl isobutyl ketone	
Dicyclopentadiene	4-Methyl-2-pentanol	

Table C--Chemicals that may autopolymerize as a result of peroxide accumulation

Acrylic acid ^b	Methyl methacrylate ^b	Vinyl chloride
Acrylonitrile ^b	Styrene	Vinylpyridine
Butadiene ^c	Tetrafluoroethylene ^c	Vinyladiene chloride
Chloroprene ^c	Vinyl acetate	
Chlorotrifluoroethylene	Vinylacetylene	

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Table D--Chemicals that may form peroxides but cannot clearly be placed in Tables A - C.

Acrolein	p-Chlorophenetole	4,5-Hexadien-2-yn-1-ol
Allyl ether ^d	Cyclooctene ^d	n-Hexyl ether
Allyl ethyl ether	Cyclopropyl methyl ether	o,p-Iodophenetole
Allyl phenyl ether	Diallyl ether ^d	Isoamyl benzyl ether ^d
p-(n-Amyloxy)benzoyl chloride	p-Di-n-butoxybenzene	Isoamyl ether ^d
n-Amyl ether	1,2-Dibenzoyloxyethane ^d	Isobutyl vinyl ether
Benzyl n-butyl ether ^d	p-Dibenzoyloxybenzene ^d	Isophorone ^d
Bexnyl ether ^d	1,2-Dichloroethyl ethyl ether	B-Isopropoxy-propionitrile ^d
Benzyl ethyl ether ^d	2,4-Dichlorophenetole	Isopropyl
Benzyl methyl ether	Diethoxymethane ^d	Limonene
Benzyl 1-naphthyl ether ^d	2,2-Diethoxypropane	1,5-p-Methadiene
1,2-Bis(2-chloroethoxy)-ethane	Diethyl ethoxymethylene-malonate	Methyl p-(n-amyloxy)benzoate
Bis(2 ethoxyethyl)ether	Diethyl fumarate ^d	4-Methyl-2-pentanone
Bis(2(methoxyethoxy)-ethyl) ether	Diethyl acetal ^d	n-Methylphenetole
Bis(2-chloroethyl) ether	Diethyketene ^f	2-Methyltetra-hydrofuran
Bis(2-ethoxyethyl) adipate	m,o,p-Diethoxybenzene	3-Methoxy-1-butyl acetate
Bis(2-ethoxyethyl) phthalate	1,2-Diethoxyethane	2-Methoxy-ethanol
Bis(2-methoxyethyl) carbonate	Dimethoxymethane ^d	Methoxy-1,3,5,7-cyclooctatetraene
Bis(2-methoxyethyl) ether	1,1-Dimethoxyethane ^d	B-Methoxy-propionitrile
Bis(2-methoxyethyl) phthalate	Dimethylketene ^f	m-Nitro-phenetole
Bis(2-methoxymethyl) adipate	3,3-Dimethoxypropene	1-Octene
Bis(2-n-butoxyethyl) phthalate	2,4-Dinitrophenetole	Oxybis(2-ethyl acetate)
Bis(2-phenoxyethyl) ether	1,3-Dioxepane ^d	Oxybis(2-ethyl benzoate)
Bis(4-chlorobutyl) ether	Di(1-propynyl)ether ^f	B,B-oxydi-propionitrile
Bis(chloromethyl) ether ^c	Di(2-propynyl)ether	1-Pentene
2-Bromomethyl ethyl ether	Di-n-propoxymethane ^d	Phenoxyacetyl chloride
B-Bromophenetole	1,2-Epoxy-3-isopropoxypropane ^d	a-Phenoxy-propionyl chloride
o-Bromophenetole	1,2-Epoxy-3-phenoxypropane	Phenyl o-propyl ether
p-Bromophenetole	p-Ethoxyacetho-phenone	p-Phenylphenetone
3-Bromopropyl phenyl ether	1-(2-Ethoxyethoxy)-ethyl acetate	n-Propyl ether

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1,3-Butadiyne	2-Ethoxyethyl acetate	n-Propyl isopropyl ether
Buten-3-yne	(2-Ethoxyethyl)-o-benzoyl benzoate	Sodium 8,11,14-eicosatetraenoate
tert—Butyl ethyl ether	1-Ethoxynaphthalene	Sodium ethoxyacetylid ^f
tert-Butyl methyl ether	o,p-Ethoxyphenyl isocyanate	Tetrahydropyran
n-Butyl phenyl ether	1-Ethoxy-2-propyne	Triethylene glycol diacetate
n-Butyl vinyl ether	3-Ethoxypropionitrile	Triethylene glycol dipropionate
Chloroacetaldehyde diethylacetal ^d	2-Ethylacrylaldehyde oxime	1,3,3-Trimethoxypropene ^d
2-Chlorobutadiene	2-Ethylbutanol	1,1,2,3-Tetrachloro-1,3-butadiene
1-(2-Chloroethoxy)-2-phenoxyethane	Ethyl B-ethoxypropionate	4-Vinyl cyclohexene
Chloroethylene	2-Ethylhexanal	2,4,5-trichlorophenoxyacetate
Chloromethyl methyl ether ^e	Ethyl vinyl ether	Vinylene carbonate
B-Chlorophenetole	Furan	Vinylidene chloride ^d
o-Chlorophenetole	2,5-Hexadiyn-1-ol	

NOTES:

^a When stored as a liquid monomer.

^b Although these chemicals form peroxides, no explosions involving these monomers have been reported.

^c 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.

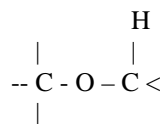
^d These chemicals easily form peroxides and should probably be considered under Part B.

^e OSHA - regulated carcinogen.

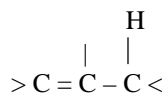
^f Extremely reactive and unstable compound.

Attachment—Peroxidizable Organic Moieties

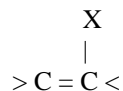
1. Ethers and acetals with α -hydrogen



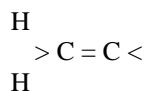
2. Alkenes with allylic hydrogen



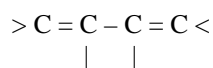
3. Chloroalkenes, fluoroalkenes



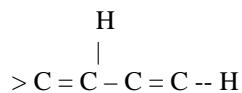
4. Vinyl halides, esters, ethers



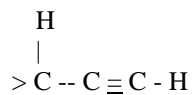
5. Dienes



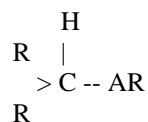
6. Vinyl alkynes with α -hydrogen



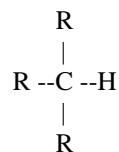
7. Alkylalkynes with α -hydrogen



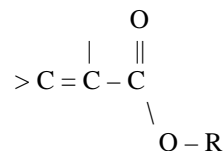
8. Alkylarenes with tertiary α -hydrogen



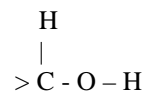
9. Alkanes and cycloalkanes with tertiary hydrogen



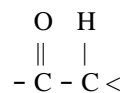
10. Acrylates, methacrylates



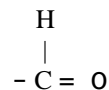
11. Secondary Alcohols



12. Ketones with α -hydrogen



13. Aldehydes



14. Ureas, amides and lactams with α -hydrogen on a carbon attached to nitrogen

