Peroxide-Forming Chemicals (PFCs)

Peroxide-forming chemicals (PFCs) are chemicals that can "auto-oxidize" with atmospheric oxygen under ambient conditions to form organic peroxides (contains an -O–O- bond). Peroxide formation can be initiated by exposure to air, self-polymerization, or solvent impurities. Once formed, organic peroxides are sensitive to thermal or mechanical shock and can be violently explosive in concentrated solutions or as solids.

Many common organic laboratory solvents, such as ethers or tetrahydrofuran, can form peroxides if not stored or used appropriately. A larger list of chemicals, including common laboratory chemicals such as isopropyl alcohol, can also form peroxides if best practices are not followed.

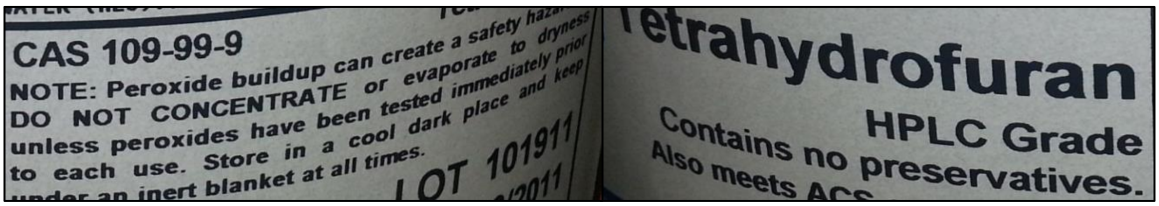

Figure 1: Example Labels with Peroxide Former Information

Identifying Peroxide Formers

According to Prudent Practices (Chapter 4.D.3.2 Azos, Peroxides, and Peroxidizables), any organic compound with a weak C–H bond is at risk for forming peroxides depending on the conditions or contaminants the chemical is exposed to. Below are some ways of identifying those compounds that are at a higher risk for peroxide formation.

- Check lists of Class A, B, C, and D peroxidizable compounds. UMN maintains an extensive list of peroxide forming chemicals with references that include any peroxide formation data and incidents reported for those compounds. Lists can also be found in Prudent Practices and from chemical manufacturers.
- Safety Data Sheets have a section titled "Hazards not otherwise classified (HNOC)" which will state "May form explosive peroxides" for many peroxide formers.
- Check container label warning statements (e.g. "NOTE: Peroxide build up can….", "Contains no preservatives", "HPLC Grade" "Stabilized" or "Inhibitor-free").

None of these methods of identifying PFCs are all-inclusive, so it's always best practice to work at the highest hazard level as a precaution and dispose of all old/expired organic chemicals through the Regulated Waste Program.

Classes of Peroxides

Peroxide formers are separated into classes (Class A-D) based on the time it takes to form explosive levels of peroxides. Below is a description of the classes along with testing and disposal requirements.

Class A: Chemicals that form explosive levels of peroxides without concentration, even when unopened.
Considerations for Class A chemicals:

- Discard within 3 months of receipt (even if unopened)

Example: Isopropyl ether, Tetrahydrofuran without inhibitor

Class B: Chemicals that are a peroxide hazard when concentrated through evaporation or distillation.
Considerations for Class B chemicals:

- Discard by the expiration date or within two years of receipt (even if unopened)
- Test for peroxide formation:
    - If intending to distill or evaporate
    - Every 6 months after opening
    - If the chemical is unopened but has been in storage for more than a year

Example: Tetrahydrofuran with inhibitor, vinyl ethers, and secondary alcohols

Class C: Chemicals that may autopolymerize without an inhibitor.
Considerations for Class C chemicals:

- Discard by the expiration date or within 2 years of receipt (even if unopened)
- Test for peroxide formation every 6 months after opening
- Class C chemicals **without inhibitors** MUST be stored under inert gas
- Class C chemicals **with inhibitors** CANNOT be stored under inert gas as the inhibitors REQUIRE oxygen

Example: Acrylic Acid, Methyl methacrylate

Class D: Additional chemicals that may form peroxides.
Considerations for Class D Chemicals:

- Discard by the expiration date or within 2 years of receipt unless the chemical quality is confirmed

Risk Assessment and Pre-Work

Risk Assessment:

Use the peroxide class lists above to help identify what chemicals are most likely to form peroxides. Keep in mind the structural properties that make peroxide formation more likely. For example, different chemical functionality can influence the ease of formation of organic peroxides (e.g. strength of C-H bonds, tendency to undergo radical self-polymerization, etc.). See Table 1 from Standard for Storing and Using Peroxidizable Organic Chemicals by Richard Kelly and Gordon Miller, to analyze structural considerations in peroxide formation.

Also consider that different physical properties can influence the ability to form dangerous concentrations of peroxides in solution. For example, compounds with a low volatility (boiling point > 300 °C or vapor pressure < 0.1 mm Hg at 20 °C) are unlikely to create dangerous (i.e. higher) concentrations of peroxides.

Considerations based on the type of PFC:

- **Grignards:** When stored in ether, the active Grignard agent acts as a stabilizer for the solvent. Once the active reagent is gone, the remaining solvent can form peroxides.

Considerations based on process:

- **Distillations and evaporation** can cause higher concentrations of peroxides, which can result in unsafe conditions if concentrated too much.
- **Columns:** Peroxides can accumulate at the top of a column if it dries out. Never run columns with PFCs that have a concentration of more than 0.5 M peroxides.
- **Low temperature work** may cause peroxides to crash out of solution if it is close to their freezing point.

Purchasing:

- Limit to what will be used within one month for Class A and others within a year.
- Select materials with peroxide stabilizers or inhibitors which serve as free-radical scavengers that terminate the chain reaction leading to peroxide formation with oxygen (e.g. butylated hydroxy toluene, also known as BHT).
- Purchase diethyl ether in metal cans where available (the metal can also inhibit peroxide formation).
- Inhibitor-free chemicals should be purchased in septum-capped bottles and stored under inert gas.

Best Practices with Peroxide Forming Chemicals

Storage:

In general, all organic chemicals should be stored away from light, tightly closed to limit exposure to oxygen and prevent evaporation, and segregated from incompatible hazard classes (e.g. oxidizers). Many manufacturers note that chemical bottle seals are only good for 2 years, so Class A, B, and C PFCs kept beyond this time limit must be disposed.

- Store away from heat and ignition sources.
- Glass storage bottles should be amber, which blocks light.
- Designate a single storage area for PFCs so none will be "forgotten" in the back of a cabinet.
- Open bottles in order of receipt and finish open containers first.
- Store inhibitor-free chemicals under an inert atmosphere.
- Only store in the refrigerator if recommended by the manufacturer and do not store at temperatures near the compound's melting/freezing point. Peroxides may crystalize or "crash out" of solution at low temperatures.

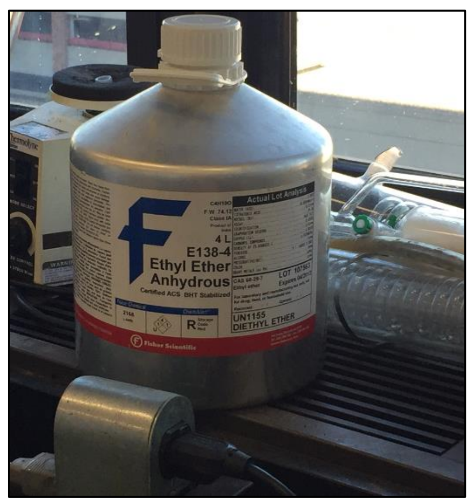

***Figure 2:** Dangerous Storage Conditions - Expired Can of Diethyl Ether Stored on a Heat Register*

Labeling:

The following information must be recorded on the label of all peroxide-forming chemicals:

- Date received
- Date opened
- Discard by date
- Peroxide test date (if open) and results

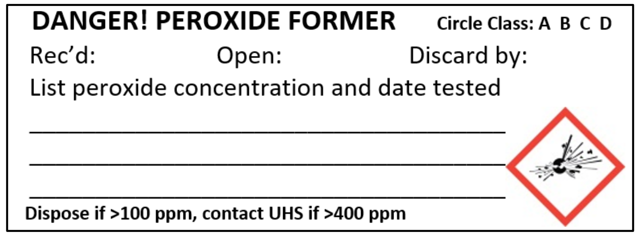

Figure 3: Sample Peroxide-Forming Chemical Label

General Work Practices:

- All researchers working with PFCs must be trained on lab-specific policies regarding safe work with PFCs.
- High-hazard procedures with PFCs (e.g. distillation) must never be performed while working alone.
- Set up a regular reminder to check for peroxides and to verify sufficient inhibitor levels.
- Visually inspect all bottles of PFCs for crystal/solid formation and other signs of deterioration before use. Use a flashlight to observe solid formation in amber bottles. If you cannot visually inspect a bottle (e.g. ether in a can) before use and suspect, err on the side of disposing it.
- Use a fume hood and a blast shield when performing higher hazard processes, such as distillation.
- Avoid procedures which involve aeration, friction, or concentration.
- Avoid metal sources (e.g. metal spatulas and magnetic stir bars) by using ceramic, Teflon, or wood when possible.
- Only dispense from original manufacturer containers. Don't reuse/refill containers, especially containers that formerly held PFCs.

High-Hazard Work Practices with PFCs

Certain high-hazard procedures may increase the likelihood of peroxide detonation (e.g. concentration, distillation, etc.). Before these procedures, always check PFCs for peroxides or impurities that could contribute to these procedures being more dangerous. Also determine whether the procedure will remove the inhibitor and determine how you will stabilize the solvent after the procedure is finished.

Safety Precautions for Distillation/Evaporation:

1. Test for peroxides before distilling; do not distill if the test shows > 20 ppm peroxides.
2. Distill under an inert atmosphere and set up your distillation apparatus with Teflon sleeves between glassware joints to reduce friction as peroxides may accumulate in glassware joint during distillation.
3. Never distill to dryness. Stop distillations of a PFC when 20% of starting volume remains or add a nonvolatile oil such as mineral oil, which ensures going to dryness is not possible and also can help dilute any peroxides formed in the distillation pot.
4. Be cautious agitating or shaking the distillation pot. Do not refrigerate/freeze the remaining solvent.
5. Distillation removes inhibitors so it is important to add an inhibitor post-distillation or sparge and store the distillate with inert gas.

Incidents

Thompson Center Explosion – UMN:
A large explosion occurred while a UHS Environmental Health and Safety Technician was processing organic waste from a laboratory cleanout. Upon disposal of an emptied glass bottle into a tip cart for recycling, a large detonation occurred in the cart (Figure 4). The most likely cause of the explosion was determined to be shock sensitive residue from a peroxide-forming chemical deposited inside an empty bottle. See the [Safety Alert] for additional details and instructions.

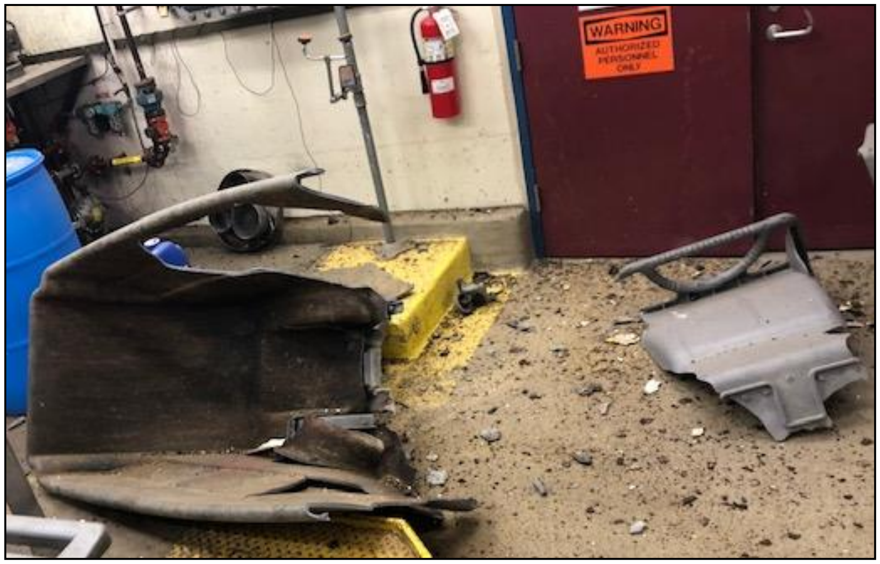

Figure 4: Damaged cart and glass fragmentation from the detonation

Methyl Methacrylate Explosion – UMN:
Quote from a researcher in the UMN Chemistry Department: “A few years back, a bottle of methyl methacrylate exploded overnight on one of our storage shelves in Smith Hall..... The only evidence that the bottle even existed was the 'puck' of polymer (Figure 5) and a small section of the bottle that included the cap and neck about 95% of the glass simply disappeared. It must have been quite the blast!”

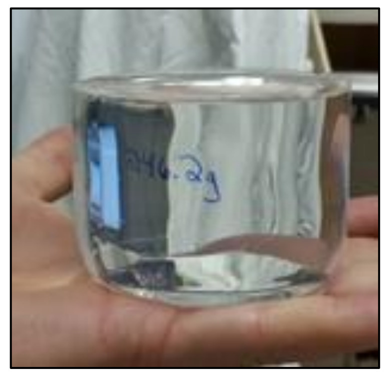

Figure 5: Polymer Puck left over from the exploded bottle

Explosion during the Distillation of Isopropyl Alcohol – N. N. Semenov Institute of Chemical Physics:
An explosion occurred during a routine distillation of isopropanol at the N. N. Semenov Institute of Chemical Physics in Moscow. After extensive studies into the cause of the explosion, it was determined that peroxides had formed during the distillation process. See their article in C&EN and the references within for more details.

Contact the Regulated Waste Program Immediately

- If crystals are visible on or in the container or lid
- If the container has a metal screw cap or glass stopper
- If a Class A compound is past its expiration date
- If a Class B or Class C compound has been open for more than 1 year and has not been tested

Do NOT open or move the container. Contact the Regulated Waste Program at (612) 626-1604 for assistance.

Testing for Peroxides

DISCLAIMER: Peroxide test results depend on the quality, age, and storage conditions of the test strips and sensitivity of the testing method. NEVER test a bottle of unknown age or quality as shock sensitive crystals may have formed in the threads of the cap and present a danger upon opening. If you are at all suspicious of a PFC, it is always best to dispose of it as hazardous waste and start with a fresh bottle.

Figure 6: Testing for Peroxides

Obtain quantitative peroxide test strips (e.g. Quantofix for Peroxide), store under recommended conditions, and check the expiration date. Follow manufacturer instructions for testing. It is always best practice to compare your test against a positive (e.g. hydrogen peroxide) and negative (e.g. n-hexanes) control. For more insight regarding the importance of using control samples, see accounts in Bretherick's Handbook of Reactive Chemical Hazards where, despite negative test results, a detonation of peroxides still occurred.

Other chemical tests that qualitatively determine the presence of peroxides are outlined in Prudent Practices, Chapter 6.G.3.2 Peroxide Detection Tests.

Basic testing procedures using strips (always follow manufacturer recommendations!):

1. Working in a fume hood, drip a sample of solvent on the test strip. Shake to evaporate excess solvent.
2. Submerge the strip in distilled water for one second and shake off excess water.
3. Determine concentration based on the color gradient on the strip container (note: reading must be taken in a timely manner) and follow the guidance in the following table.

Peroxide Concentration	Instructions
Under 20 ppm	The solvent is safe for use
Between 20 and 100 ppm	The solvent should not be distilled or concentrated
Between 100 ppm and 400 ppm	The solvent must be disposed of as waste
Above 400 ppm	Immediate UHS assistance and evaluation is needed

Inactivating Peroxides

Inactivating peroxides is not recommended. Besides the risk of the peroxides themselves, the inactivation techniques often employ heat, concentration or additional hazardous reagents making the process riskier than simply disposing and purchasing new reagent. A risk assessment with your assigned Research Safety Professional is required before this process will be approved.

Disposal

All peroxide-formers must be disposed of as hazardous waste. You are not required to test for peroxides if you are not comfortable doing so, simply state in your disposal request that the solvent has not been tested and note the approximate age of the bottle.

Materials with peroxide concentrations < 400 ppm can be disposed following standard waste procedures.

- Indicate the peroxide concentration on the request form
- Don't mix peroxide containing solvents with other waste streams
- Add a dash of additional inhibitor prior to disposal, if you have it

Materials with peroxide concentrations > 400 ppm MUST be evaluated by UHS to determine the safest method for disposal. Do not move the container and contact the Regulated Waste Program at (612) 626-1604 for assistance.

UMN Resources

Consultations and hazard assessments can be performed with the Research Safety Professional assigned to your area or contact the University Health and Safety main office at (612) 626-6002 or uhs@umn.edu.

References and Further Reading

If you do not have access to one of these resources, contact your Research Safety Professional for more information.

- NRC Prudent Practices – Chapter 6.G.3 Organic Peroxides
- Bretherick's Handbook of Reactive Chemical Hazards (See UMN Library for access if link doesn't work)
- Standard for Storing and Using Peroxidizable Organic Chemicals by Richard Kelly and Gordon Miller
- Kelly, R. J. 1996. Review of safety guidelines for peroxidizable organic chemicals. Journal of Chemical Health and Safety 3 (5), 28-36
- Mason, D., Those Pesky Peroxides…, Journal of Chemical Health and Safety 2014, 21 (3), 13.
- Clark, D., Peroxides and Peroxide - Forming Compounds, Journal of Chemical Health and Safety 2001, 8 (5), 12-21. (Also See Peroxides and Peroxide-Forming Chemicals, Clark, Brookhaven National Laboratory)
- Millipore Sigma Learning Center – Peroxide Forming Solvents
- Chemical Safety: Peroxide formation in 2-Propanol (C&EN)
- Safety Alert: Dangers of Peroxide Formers – Explosion at UMN