The use of alternative solvent purification techniques

A recent accident at the University of California, Irvine involved the purification of an organic solvent using a solvent still resulting in a fire in the lab. A graduate student was seriously burned and $3.5 million in property damage was incurred. In this report, lessons learned from this accident are used to improve the safety of solvent purification operations. Column methods of aprotic solvent purification processes, as well, as the purchasing of ultra-dry organic synthesis solvents are evaluated. Residual risks associated with the solvent still operation are compared with the alternative purification methods. While severity remains unchanged using the column method, employing the column method reduces the likelihood of an accident. For most applications, the column method and the purchase of ultra-dry solvents remove moisture and oxygen at least to the same level as the solvent still method. This is not without additional costs. Column systems have higher upfront capital costs and ultra-dry solvents cost 20–50% more than certified solvents. Cost–benefit analysis argues that the additional costs make alternative purification methods acceptable. In conclusion, column methods of aprotic solvent purification processes and the purchasing of ultra-dry organic synthesis solvents are, in many applications, a cost-effective alternative to solvent stills for producing a moisture- and oxygen-free product.

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INTRODUCTION

In order to obtain satisfactory results in many syntheses involving air moisture sensitive reactions, it may be necessary to purify solvents to remove reactive impurities such as water, other protic/acidic materials, or atmospheric contaminants such as oxygen. A commonly employed purification method is the solvent still, which involves the reflux/distillation of an organic solvent in the presence of a dehydrating/deoxygenating reagent. A recent accident at the University of California, Irvine (UCI) involved the purification of an organic solvent using a solvent still.[1] The consequence of the accident was a fire in the lab that seriously burned a graduate student, and caused $3.5 million in property damage. An accident of this magnitude warrants an evaluation of this traditional method of purification to assess the adequacy of the control measures currently in place and to consider alternative methods of producing a quality solvent. In 1996, the column method of solvent purification was introduced which eliminates hazards associated with distillation.[2] This report consists of a critical evaluation of solvent still and column methods of aprotic solvent purification processes, as well, justification for the purchasing of ultra-dry organic synthesis solvents.

Since the sodium benzophenone ketyl solution is among the most common solvent still methods to prepare pure, anhydrous, oxygen-free solvents, it will be used as an example. Typically, an organic solvent is refluxed in the presence of sodium and benzophenone in an inert atmosphere, as shown in Figure 1. The reactive metal removes moisture from the solvent, and the ketyl intermediate that forms upon reaction of the ketone and the metal acts as an oxygen scavenger. The blue color of benzophenone ketyl is used as an indicator that the solvent is ready for use. Usually the reflux process is continued for several hours to ensure solvent purity.

Alternatives to the traditional solvent still include the column method in which dry nitrogen or argon is used to force commercially purified solvents through a stainless steel column. The column is packed with activated alumina and copper catalysts to remove trace amounts of water (Figure 2). Alternatively, the solvent must be run through a bubble degassing process when not suited for copper catalyst oxygen removal. Last, if only small quantities of pure anhydrous solvent are needed, it is sometimes considered more cost effective to buy these solvents directly from a supplier.

TECHNICAL VALIDITY

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level as the solvent still method. Qualitatively, both the column method and the purchase of ultra-dry solvents meet the tests for assessing oxygen and protic contaminants by using the sodium benzophenone-ketyl test or titanocene dichloride/zinc dust test. Quantitative values are shown in Table 1.[3]

Figure 1. A typical solvent still.

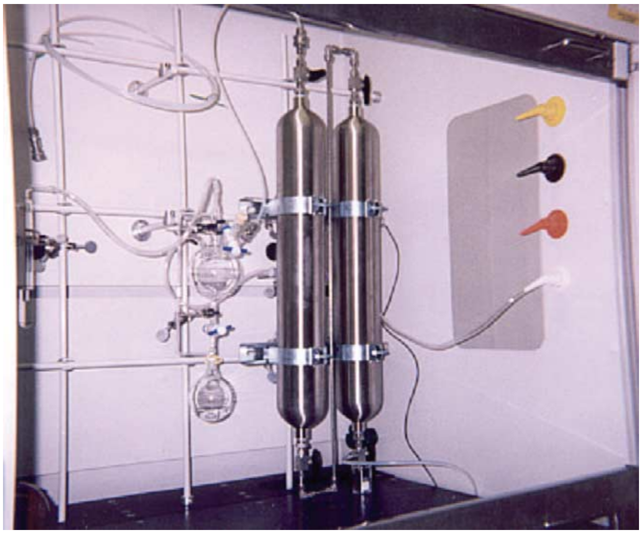

Figure 2. A commercially available column system.

Table 1. Quality of Purified Solvent

	Impurities		
Method	Water (ppm)	Oxygen (ppb)	Peroxides (ppm)
Solvent still	10	100	<1
Column	<1[4]	10000	<2
Purchasing	5	<100	<1

RISK

The risk associated with the purification of an organic solvent is a function of the likelihood and potential severity of injury, harm, incurred liability, damage or loss. As the accident at UCI clearly illustrated, the primary consequences (severity) associated with purifying flammable solvents are injuries and property losses due to fire and explosions. It should be noted that the severity remains unchanged using the column method.

The main difference in risk between the solvent still and column method is in the likelihood of an accident. Procedures reacting active metals and flammable liquids, such as sodium and most organic solvents increase the likelihood that a fire or an explosion will occur. This is not limited to the purification procedure, but extends to the quenching of spent sodium for disposal, as well. The likelihood of an explosion or a fire increases further with the nearness of the following ignition sources: heating mantles, vacuum pumps, and water lines from condensers and the high temperatures needed for distillation. Stills with automatic controls that shut down the system conditions, such as loss of cooling or overheating of the still pot, do enhance the safety of the distillation operation greatly.

While the column method has none of these fire or explosion initiators, it introduces some hazards of its own. Since the columns are pressurized (5–50 psi), a stored energy hazard is present. Peroxides may accumulate on the columns, as well, introducing an explosive hazard. In addition, the column method does involve larger quantities of solvent.

DISCUSSION

With several prominent universities and companies using the column method to purify organic solvents, the ppm level of oxygen is not an issue with most air and moisture sensitive reactions. On the other hand, the copper catalyst is incompatible with some solvents including tetrahydrofuran and methylene chloride. Oxygen must be removed from these solvents by purging them with dry nitrogen or argon. Thus, column method is a valid substitute for the solvent still method within limits.

Table 2. Risk Determination Matrix

	Likelihood				
Severity	Frequent	Probable	Occasional	Improbable	Remote
Catastrophic	High	High	High	Medium	Low
Critical	High	High	Medium	Low	Minimal
Moderate	High	Medium	Low	Minimal	Minimal
Negligible	Low	Minimal	Minimal	Minimal	Minimal

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The main goal of implementing a process improvement is to decrease the risk to an acceptable level associated with abnormal occurrences from the purification of an organic solvent. The first issue that this raises is whether solvent stills with their current set of controls are processes that can be run with an acceptable level of risk. An objective method of determining risk with hazardous material operation may be obtained using the risk matrix from the paper titled "A Risk Determining Model for Hazardous Material Operations," as shown in Table 2.[5] Clearly, the severity of the accident that occurred at the UCI is rated "Catastrophic" due to the magnitude of the property damage. It should be noted that several factors contributed to the immediate consequences of the accident, including the following:

- The quantities of flammable and combustible liquids present in the building at the time of the fire were in excess of the quantities allowed for B-2 occupancy by the 1979 Building Code.
- The door (with a 1-hour-rated fire door with self-closing and positive-latching hardware) between the laboratory with the solvent still and a room filled with flammable and combustible liquids was blocked open.
- Automatic sprinkler system protection was not installed.

The fact that this should not have happened during the life of the facility, but did, gives it likelihood rating of "Occasional." Similar accidents have occurred at the University of California at Berkeley in 1996 and the University of Texas at Austin in 1997. These observations lend further validity to the "Occasional" likelihood rating.[6]

Using the matrix, the residual risk (the risk remaining after controls are in place, with consideration of reliability and certainty of the controls and risk of control failure) associated with a solvent still is high. Whether operation with high residual risk should be authorized (acceptable) is the responsibility of line management. While this judgment is determined in a case-by-case study, UCI hopes to replace 30 chemical distillation devices with columns.[7] The column method lowers the likelihood to a remote level during the purification. Hence, the residual risk associated with the column method is low (acceptable).

The second issue that implementing a process improvement raises is whether the cost is acceptable. Many emerging technologies may be technically sound and lower the risk associated with the process they seek to improve and yet may be economically unacceptable. From a business viewpoint, the acceptable level may be achieved when the costs of decreasing a given risk further are greater than the costs realized from the occupational exposure to hazardous chemicals. Tangible costs for implementing technologies that lower risk in a chemical operation have not been published. On the other hand, criteria for establishing cost-effective dose-reduction measure are well established for the nuclear industry.[8] Cost–benefit analyses typically apply monetary equivalents of \$1,000 to \$10,000 per person-rem with the recommended nominal value being \$2,000 per person-rem. Optimization analysis are performed whenever the cost of these measures exceeds \$50,000 or the collective dose to be avoided is greater that 5 person-rem. In addition, the cost incurred from radiological exposures have been compared to other non-radiological accidents including property losses, as shown in Table 3.[9]

Using the UCI accident as an example, the following approach is taken to obtain a reasonable cost–benefit analysis between the two methods of solvent purification:

Table 3. Criteria that Trigger an Unusual Occurrence

Groups of Unusual Occurrences	Criteria
Facility condition: loss of control of radioactive material or spread of radioactive contamination[*]	>100,000 (dpm)/100 cm^2
Personnel radiological protection: radiation exposure	>5 rem[**]
Value Base Reporting: cost-based occurrences	=\$1,000,000

[*] dpm = disintegrations per minute.

[**] rem = Roentgen equivalent man.

1. An accident resulting from a solvent still operation is classified as a cost-based occurrence.
2. The UCI accident is rated as an "Unusual Occurrence" in the Value Base Reporting category because over 1 million dollars in property damage occurred.
3. This type of occurrence is categorized at the same level as a radiation exposure of greater than 5 Roentgen equivalent man (rem), as shown in Table 3.
4. Recommended nominal value of \$2,000 per person-rem typically is applied.

Using this recommended nominal value, over \$10,000 could be spent on process improvements to reduce the likelihood of fire and explosion hazards and still be cost-effective.

Furthermore, a study conducted by the University Wisconsin, Madison (UWM), concluded that over the long term the column method cost less.[10] Results of cost comparison of the solvent still and column methods are compiled in Table 4. While the column method has a higher set up cost, the annual operating are lower.

The quality of the distilled product needs to be considered. For most purposes (e.g., Grignard reactions) the use of common inorganic drying reagents such as anhydrous magnesium sulfate, $MgSO_4$ (stirred overnight and filtered) are sufficient. The UWM study also concluded that the column method was an ineffective choice for purifying tetrahydrofuran.

Another alternative is the purchase of pure anhydrous solvent. In the past, if only small quantities of pure anhydrous solvent were needed, it was sometimes considered more cost effective to buy these solvents directly from a supplier. Cost increase varies per solvent, but in general the cost of an anhydrous solvent is two to three times that of a certified American Chemical Society (ACS) solvent and costs of standard high purity solvents are 20–50% more expensive than that of certified ACS solvents.[11] Depending on volumes, required costs vary. Once operating costs of the solvent stills, the capital costs of the column, and the liability of both the purification methods are weighed; the additional costs seem more reasonable.

Table 4. Solvent Purification Cost Comparison

Method	Set Up Costs (\$)	Annual Operating Costs (\$)
Solvent still	4800	4000
Column	6300	100

Last, the larger quantities of solvent and peroxides on the used adsorbent associated with the column method must be addressed. The larger quantities of solvent are contained in metal cans, which are safer than glass bottles. Since the peroxides remain unchanged on the alumina, the used adsorbent should not be heated. Stirring the adsorbent into an iron sulfate solution can mitigate the peroxide hazard or spent columns can be sent back to the manufacturer for regeneration.

CONCLUSIONS

The results of this study demonstrate that distillation and purification of flammable solvents, using the solvent still method, will continue to be an integral part of chemical experimentation, if only on a limited basis as alternative methods become available. Active metals increase the likelihood of an explosion and fire with flammable liquids. In the past the solvent still method of purifying organic solvents had an acceptable level of risk because there was no alternative way of obtaining a moisture- and oxygen-free product. Column methods of aprotic solvent purification processes, as well, as the purchasing of ultra-dry organic synthesis solvents are now cost effective alternative way of obtaining a moisture- and oxygen-free product.

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