Risk of Fire and Health Hazards Due to Organic Solvents in Chemical Laboratories

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ABSTRACT

This report comprehensively explores the risks of organic solvents as both fire and health hazards based on the results of “working environment measurements”, as specified in Japan’s safety and health laws. The results in 2018 and 2019 in our chemical laboratory determined that the lids of many waste solvent containers were open, which may potentially result in both fire and health hazards. When organic solvents volatilize to fill a laboratory, the vapor may be markedly harmful to human health. Although the conditions in our laboratory have improved by 2020, our laboratory mainly uses methanol and acetone, both of which are highly flammable and could ignite to cause a fire. It should be noted that vaporizing liquid organic solvents and other gases are not under the purview of the Fire Service Act on Hazardous Materials (in Japan), which is limited to condensed or liquid phases with ignition and explosive properties. In this context, herein, we summarized the health hazards and fire hazards of organic solvents (category 4), including methanol, acetone and N,N-dimethylformamide, by analyzing the results of working environment measurements in our laboratory over a period of several years. From the perspective of health and fire safety, it is imperative to focus on strategies to mitigate the risks of organic solvents in chemical laboratories. The correlation of both aspects is also discussed based on the results.

Keywords: Chemistry, Laboratory, Organic Solvents, Fire, Hazards

1. INTRODUCTION

In recent years, accidents involving organic solvents have occurred frequently in chemical laboratories. For example, a Japanese government (Ministry of Health, Labor, and Welfare) website reports methanol poisoning in the chemical industry in 2019 and acetone poisoning in the electrical equipment industry in 2017, which were caused by insufficient ventilation and a lack of sufficient time for laboratory workers to put on gas masks. In addition, in 2009, a fire resultant from an organic solvent containing acetone occurred in the plastic product manufacturing industry, with one fatality. The
precise cause of the fire was believed to be an exothermic reaction during the mixing of the solvent, which ignited combustible materials. The underlying cause of the accident, however, was the lack of an appropriate instruction manual and insufficient directions from the work supervisor.

Efforts must be made to design laboratories with focused attention given to risk reduction. To avoid such accidents due to chemicals, “working environment measurements” must be implemented in chemical factories and laboratories. For example, volatile organic solvents with low flash point such as THF and diethylether are easy to ignite actually. In 2018 and 2019, our chemical laboratory determined that the lids of many waste solvent containers were open, which could potentially result in both fire and health hazards. When organic solvents volatilize to fill a room of a chemical laboratory, the vapor may be seriously deleterious to human health. This hazardous situation, however, has been substantially improved in our laboratory by 2020. In this study, we discuss the risks of health hazards and fire hazards caused by organic solvents based on the results of working environment measurements. From the viewpoint of health and fire safety, it is urgent that the risks of organic solvents in chemical laboratories be comprehensively addressed. The correlation of both aspects will also be discussed based on the results.

2. SURVEY METHODS

The data source of “working environment measurements” in the Akitsu Laboratory (inorganic chemistry), Department of Chemistry, was obtained in December 2018, July 2019, January 2020, and December 2020 by the Tokyo University of Science at regular intervals according to the method stipulated by law. Article 2 of the Industrial Safety and Health Law in Japan defines “working environment measurement”, classified into measurements A and B, as the design, sampling, and analysis of the air environment and other working environments to ascertain the actual conditions of the working environment. Specifically:

A: To measure the average concentration of the hazardous substance in the unit workspace.
B: To measure the expected maximum concentration of the hazardous substance at a specific time and location of the unit workspace (sampling points in the Akitsu Laboratory y, a circle is marked in Figure 1).

In addition, cross-checking is conducted periodically for accuracy control to continuously improve measurement accuracy. The following 18 items were investigated [1]:

1. Organizing and tidying-up: organizing equipment, supplies, waste, etc.
2. Evacuation routes: securing proper evacuation routes.
3. Tipping-over prevention measures: determining if the laboratory equipment is adequately prevented from tipping-over or falling by itself.
4. Disaster prevention equipment: preparation of sufficient fire extinguishers and emergency lights.
5. Emergency contact system: establishment of an effective emergency contact system.
6. Fire: whether or not combustible materials are in the area.
7. Smoking: whether or not there is a designated smoking area.
8. Waste: whether or not waste is separated and disposed of according to stipulated rules.
9. Electrical equipment: whether or not there is excess capacity, scattered wiring, etc., in the workspace.
10. Chemical management: whether or not appropriate chemical treatment is being carried out.
11. High pressure gas: whether or not effective measures are in place to prevent tipping-over of high-pressure gas containers, and whether all piping is appropriate.
12. Radiation/radioactive materials: whether or not such materials are properly controlled in strict accordance with radiation damage prevention regulations.
13. Local exhaust system: whether or not organic vapor is always drawn off.
14. Laser: whether or not there is a display at the entrance and exit of the workspace that indicates that there are one or more laser devices on the premises.
15. Unmanned operation equipment: whether or not sufficient safety measures for such equipment are implemented.
16. Large machine tools: whether or not appropriate protective equipment is worn when working with such tools.
17. Cranes: whether or not cranes are operated by qualified personnel who are fully qualified regarding both the equipment and particular operation.
18. Other hazardous materials: whether or not appropriate safety measures are in place concerning such materials.

3. RESULTS

3.1 Laboratory Layout

Figure 1 shows the layout of the Akitsu Laboratory, in which there are two draft chambers and two air conditioners with a ventilation system in the ceiling. Among the three entrance/exit doors, only one (lower right in Figure 1) is open and frequently used. Although the upper air conditioners were turned off during the sampling of gases in the room, airflow was stagnant in five places in the "working environment measurement". This ⬤ mark indicates the airflow stagnation state.
3.2 Results of Work Environment Measurement

Table 1 presents the results (vapor of organic solvents) of work environment measurements in the Akitsu Laboratory in 2018, 2019, and January and December 2020. The substances measured were acetone, methanol and N, N-dimethylformamide, all of which are in a control classification of I. The control concentration was $E = 1$ (dimensionless), except for 2019, because the concentration of ethanol was described for 2019. Because of the non-experimental working space around the upper left door, detection of volatile solvents in this area may be attributed to exposure, depending on airflow.

The lids of some liquid waste tanks were left open, and thus high risk was recorded in 2019. When handling volatile organic substances as experimental reagents, experimental operations are conducted in the draft chamber, in general. The suction air speed of the draft chamber was 0.40-0.46 and 0.42 m/s (both at 35 cm height of the opening surface), and so an appropriate suction air speed was maintained compared to the legally specified air speed of 0.4 m/s. The smoke tester indicated no leakage of gases outside of the draft chamber in such situation. Although the methanol and acetone used for cleaning laboratory glassware are kept in cleaning bottles, a possibility of leakage exists due to temperature and pressure changes.
Table 1 Results (dimensionless) of work environment measurement conducted in the Akitsu Laboratory

|       | July 2018 | December 2018 | July 2019 | December 2019 | December 2020 |
|-------|-----------|---------------|-----------|---------------|---------------|
| A     | 0.09      | 0.1           | 0.05      | 0.12          | 0.19          |
| B     | 0.09      | 0.1           | 0.05      | 0.1           | 0.26          |

In addition, using the MHLW's risk assessment support tool (CREATE-SIMPLE) from 2020, risk assessment measurements of chemical reagents owned by the Akitsu Laboratory were also conducted and determined to be Level 1 at the same time as the working environment measurements. For the top three reagent groups in terms of the amount of each substance handled, there are two types: "Handle in the laboratory 3 times a week for about 1 to 2 hours" and "Handle in the draft 3 times a week for about 1 to 2 hours". Tables 2 - 7 below show the risk assessment in one situation. The qualitative levels of (health) hazards and (fire or other accident) dangers are as follows:

1. Working environment is sufficient.
2. Working environment is good.
3. Action is required to reduce risk.
4. Immediate action is required to reduce risk.

The situation of higher risk level (1 < 2 < 3 < 4) of solvent vapor with harmful effects on the eyes or skin will also lead to a fire accident due to ignition.

Table 2 Amount of reagents owned (amount handled) No. 1 Risk assessment results when handling the target substance in the laboratory for 1 to 2 hours, 3 times per week

| Substance                          | Transaction volume (kg/month) | toxicity | hazardous | skin |
|------------------------------------|------------------------------|----------|-----------|------|
| Potassium cobalt cyanide           | 0.0037                       | 4        | 1         | S    |
| Dipotassium nickel(II) tetracyanide| 0.0037                       | 3        | 1         | S    |
| Cobalt(II) acetate tetrahydrate    | 0.01                         | 3        | 1         | S    |
| Copper(II)pyrophosphate            | 0.042                        | 2        | 1         | S    |
| p-Cresol                           | 0.044                        | 3        | 1         | S    |
| Di-n-butylphosphate                | 0.0063                       | 3        | 1         | S    |
| Cadmium oxide                      | 0.00042                      | 4        | 1         | S    |
| Sodium sulfide                     | 0.021                        | 3        | 2         | S    |
| Phosphorus pentasulfide            | 0.041                        | 2        | 3         | S    |
| Titanium(IV)oxide                  | 0.044                        | 3        | 1         | S    |
| Potassium silver cyanide           | 0.00034                      | 4        | 1         | S    |
| α-Phthalodinitrile                 | 0.0021                       | 4        | 1         | S    |
Table 3  Amount of reagents owned (amount handled) No. 1 Risk assessment results when handling the target substance in the draft for 1 to 2 hours 3 times a week

| Substance                               | Transaction volume (kg/month) | Risk assessment |   |   |   |
|-----------------------------------------|-------------------------------|----------------|---|---|---|
| Potassium cobalt cyanide                | 0.0037                        | 1              | 1 |  - |   |
| Dipotassium nickel(II) tetracyanide     | 0.0037                        | 1              | 1 |  - |   |
| Cobalt(II) acetate tetrahydrate         | 0.01                          | 1              | 1 |  - |   |
| Copper(II)pyrophosphate                 | 0.042                         | 2              | 1 |  S |   |
| p-Cresol                                | 0.044                         | 2              | 1 |  S |   |
| Di-n-butyl phosphate                    | 0.0063                        | 1              | 1 |  S |   |
| Cadmium oxide                           | 0.00042                       | 1              | 1 |  S |   |
| Sodium sulfide                          | 0.021                         | 1              | 2 |  S |   |
| Phosphorus pentasulfide                 | 0.041                         | 1              | 3 |  S |   |
| Titanium(IV) oxide                      | 0.044                         | 1              | 1 |  S |   |
| Potassium silver cyanide                | 0.00034                       | 1              | 1 |  S |   |
| o-Phthalodinitrile                      | 0.0021                        | 2              | 1 |  S |   |

Table 4  Amount of reagents owned (amount handled) No. 2 Risk assessment results when handling the target substance in the laboratory for 1 to 2 hours 3 times a week

| Substance                 | Transaction volume (kg/month) | Risk assessment |   |   |   |
|---------------------------|-------------------------------|----------------|---|---|---|
| Dichloroacetic acid       | 0.0021                        | 4              | 2 |  S |   |
| Terephthalic acid         | 0.042                         | 3              | 1 |  S |   |
| Diphenyl ether            | 0.042                         | 3              | 1 |  S |   |
| Diphenyl ether            | 0.25                          | 2              | 1 |  S |   |
| Ethyl formate             | 0.042                         | 3              | 2 |  S |   |
| Tetrachloroethylene       | 0.042                         | 3              | 1 |  S |   |
| Vinyl chloride polymer    | 0.042                         | 4              | 1 |  S |   |
| Chloroacetic acid         | 0.042                         | 3              | 1 |  S |   |
Table 5  Amount of reagents owned (amount handled) No. 2 Risk assessment results when handling the target substance in the draft for 1 to 2 hours 3 times a week

| SUBSUTANCE          | transaction volume | risk assessment |
|---------------------|--------------------|-----------------|
|                     | (kg/month)         | toxicity | hazardous | skin |
| Dichloroacetic acid | 0.0021             | 4        | 2         | S3   |
| Terephthalic acid   | 0.042              | 3        | 1         | S    |
| Diphenyl ether      | 0.042              | 3        | 1         | S    |
| Diphenyl ether      | 0.25               | 2        | 1         | S    |
| Ethyl formate       | 0.042              | 3        | 2         | S    |
| Tetrachloroethylene | 0.042              | 3        | 1         | S    |
| Vinyl chloride polymer | 0.042         | 4        | 1         | S    |
| Chloroacetic acid   | 0.042              | 3        | 1         | S4   |

Table 6  Amount of reagents owned (amount handled) No. 3 Risk assessment results when handling the target substance in the laboratory for 1 to 2 hours 3 times a week

| Substance            | Transaction volume | Risk assessment |
|----------------------|--------------------|-----------------|
|                      | (kg/month)         | toxicity | hazardous | skin |
| p-Phenylenediamine   | 0.0021             | 3        | 1         | S    |
| Paraquat             | 0.00036            | 3        | 1         | S    |
| Aniline              | 0.083              | 4        | 1         | S    |
| 2.6-Xylidine         | 0.0042             | 3        | 1         | S    |

Table 7  Amount of reagents owned (amount handled) No. 3 Risk assessment results when handling the target substance in the draft for 1 to 2 hours 3 times a week

| Substance            | Transaction volume | Risk assessment |
|----------------------|--------------------|-----------------|
|                      | (kg/month)         | toxicity | hazardous | skin |
| p-Phenylenediamine   | 0.0021             | 3        | 1         | S3   |
| Paraquat             | 0.00036            | 1        | 1         | S    |
| Aniline              | 0.083              | 2        | 1         | S    |
| 2.6-Xylidine         | 0.0042             | 1        | 1         | S    |
4. DISCUSSION

4.1 Vapor of Organic Solvent inside/outside of a Draft Chamber

According to the working environment measurement reports in 2018 and 2019, the lids of many liquid waste containers were open. By 2020, however, this situation in our laboratory has been greatly improved. A few main organic solvents were used in the Akitsu Laboratory, and these were also used outside of the draft chamber because methanol and acetone, in particular, are used to wash glassware. When handling these organic solvents, we can greatly prevent health hazards by avoiding skin contact and ingestion by wearing sanitation clothing and protective eyewear. Both of these organic solvents are highly flammable, and if they are left open and exposed, there is a substantial probability that the vaporized organic solvents will ignite and cause a fire. The health and fire hazards of the organic solvents assessed according to the working environment measurements are described in the following.

Methanol results in various major health hazards, such as strong eye irritation, harmful if ingested, possible adverse effects on fertility or the unborn child, drowsiness and dizziness, organ damage (central nervous system, visual organs, systemic toxicity), and organ damage (central nervous system, visual organs) due to long-term or repeated exposure. Moreover, a fire hazard exists due to highly flammable liquid and vapor [2].

Acetone also poses various serious health hazards, including eye irritation, possible adverse effects on fertility or the fetus, possible irritation to the respiratory tract, possible drowsiness or dizziness, and organ damage (central nervous system, respiratory system, gastrointestinal tract) due to long-term or repeated exposure. In addition, a fire hazard exists due to highly flammable liquid and vapor [3].

N, N-dimethylformamide results in various health hazards, including serious eye damage, toxicity if inhaled, suspected hereditary disease, possible carcinogenesis, possible adverse effects on fertility or the unborn child, possible organ damage (respiratory system), and organ damage (liver) due to long-term or repeated exposure. Furthermore, a fire hazard exists because it is a highly flammable liquid and vapor [4].

According to the risk assessment of reagents in the laboratory [5], handling the reagents in a draft, we found from Tables 2 and 3 that most reagents handled in large quantities in the laboratory can improve the risk. But, the handling of dichloroacetic acid, chloroacetic acid, and p-phenylenediamine was considered high risk, even in a draft chamber. Comparing Tables 4 and 5 for dichloroacetic acid and chloroacetic acid, and Tables 6 and 7 for p-phenylenediamine, the risk to the eyes and skin is low when handled in the laboratory, but becomes a high risk when used in a draft chamber due to the air circulation within it. Draft chambers have a high risk of reagents "flying" because of the constant air intake. In addition, since the draft chamber is an enclosed space, there is a high risk of the reagents adhering to the arms or other parts of the body if one puts one's hands in the air, although the hands will be protected if they are covered by protective clothing.
4.2 Materials Safety Data Sheets (SDS)

The organic solvents methanol and acetone, which are frequently used in our laboratory, belong to class 4. Although the above can be applied to liquids, it should be noted that the Fire Service Law Hazardous Materials (in Japan) are limited to condensed phases with ignition and explosive properties, and gases are not included. In our laboratory, it is a rule to submit an experimental plan and (materials) safety data sheets ((M)SDS) when purchasing new reagents, so that the characteristics of hazardous substances can be fully understood and addressed prior to conducting experiments.

The information in the SDS includes not only the name and physicochemical properties of the chemical contained in the chemical product, but also the hazards, toxicity, first aid measures, safe handling instructions, storage, disposal methods, etc. Indeed, from the information in the SDS, certain fire accidents can be predicted. However, some accidents cannot be predicted with the SDS.

Certain accidents occur due to human error. For instance, an explosion took place during the production of a food additive from seaweed by scraping powder off of a reaction vessel using a spatula at a facility. Specifically, organic solvents, such as methanol and seaweed extracts, entered the reaction vessel [6] and exploded when the powder was being scraped off of the vessel. Overall, the accident was caused by static electricity buildup due to the rotation of the container. The spatula was made of polyvinyl chloride, and the blade was attached to the handle by a metal bolt. The immediate cause of the accident was ignition of vapor due to electrostatic discharge. The substance that produced this accident was a flammable liquid of hazardous material class 4. In order to safely experiment with these substances, it is necessary to maintain a requisite distance from the fire source.

As mentioned above, it is worth noting and reflecting on the fact that the cause of the accident is that the rules of course are not followed. These organic solvents are actually used in the laboratory, and especially methanol is also used for cleaning instruments, so it is necessary to handle it with care on a daily basis. When handling these organic solvents, it is possible to prevent health hazards by preventing them from adhering to the skin or being taken into the body, such as by wearing sanitary or protective goggles. There are no other major problems if you handle it with care, but if the lid of the waste liquid tank is left open, these organic solvents will volatilize and fill the laboratory, which will lead to health hazards. Therefore, it is necessary to take care such as keeping the lid of the waste liquid tank closed except when using it. In addition, the risk of fire can be prevented by not using these organic solvents in the presence of fire.

5. CONCLUSION

In this study, we mainly analyzed the results of working environment measurements in the Akitsu Laboratory to elucidate to what extent the hazards of organic solvents can
be avoided. In addition, we explored non-obvious risks of toxicity that must be avoided.

Various major hazards exist in chemistry laboratories. As a consequence, it is crucial for laboratory workers and students to possess sufficient knowledge of the properties of hazardous substances, and how to deal with fires and danger to human life when conducting research in laboratory settings. Indeed, it is necessary to provide thorough safety lectures on these issues to students with little previous research experience. In the following, we specify the two main requisite contents of such safety lectures on the hazards and fire risks of organic solvents.

In order to avoid the risks of organic solvents in the future, it is the case that artificial intelligence may be increasingly and effectively used. However, determination of how to solve cases of human error due to human judgment remains both complicated and unclear. Therefore, it is critical to reduce the risk of fire as much as possible by firstly reviewing the hazards of organic solvents during daily experiments, and secondly raising awareness of the need to thoroughly submit experiment plans and SDSs.

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