Boring but Vital – How Should We Teach Our Students About Chemical Safety?

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Abstract. *One of the most important considerations in the operation of a science laboratory is safety. This paper discusses why an understanding of safety issues in the laboratory is as vital as a knowledge of the science itself, and suggests a number of ways of promoting an appreciation of safety issues among students.*

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1. Introduction

Safety should be an influence on every aspect of the way that science is taught, both at school and in College or University. However, while this is easy to state, it is not always easy to put into practice.

All competent science teachers appreciate the importance of safety, but students may regard it as an irrelevance, or as an inconvenience that gets in the way of "real" science. They might be required to wear a lab coat and use safety glasses in the laboratory, but only comply with these rules because they are mandatory. Students tend, especially in their teens, to doubt the need for protection from chemicals, and to be particularly uninterested in protection from themselves and from their co-workers. By contrast, school administrators may take exactly the opposite position, fearing litigation were an accident to occur in a laboratory in which safety precautions were not being followed to the letter.

Both students and administrators may, for quite different reasons, see safety as a separate matter from the underlying science. In fact, science and safety are inextricably linked, as several case studies in this paper will illustrate. These case studies are drawn from a variety of real incidents reported on the media or on the Internet. In most cases those concerned have deliberately not been identified.

1.1. Case Study A

A chemistry laboratory activity on the web describes a potentially valuable exercise for science students in a high school. Groups of students are given a hypothetical budget of $20,000, and are then issued with promotional literature and catalogues from science suppliers. Their task is to furnish from scratch an imaginary science laboratory.

Among the stated aims of the exercise is that the students should "...review the safety equipment needed for a chemistry lab", which suggests that safe working will be a key consideration. However, in the exercise no indication is given about how safe working within the laboratory could be promoted.

In fact, the task of buying equipment for the imaginary laboratory appears to be completely detached from its subsequent operation, though in fact the two should be closely linked; safety should influence the purchasing decisions at every stage.

This exercise is potentially valuable. It would be regarded as an interesting challenge by typical students, but the way that it is presented plays down the importance of safety. The exercise may give students the impression that safety is an extra that can be bolted on once laboratory design is complete. This is an unfortunate - and potentially dangerous - view.

2. Integration of safety into teaching

Safety should be a part of everything that we do in the practical science laboratory. In this paper, we consider first the principle reasons why safety is so crucial in the school laboratory, beginning with the most obvious reason – the need to avoid accidents.

2.1 Safe practice

It is clear that chemistry students, and those who study other subjects but must use chemicals in their practical work, need to learn about chemical hazards so that they can carry out experiments safely. Instruction designed to ensure safe working not only protects students, but also the school in the unfortunate event of an accident. Case Study B illustrates how inadequate or inappropriate preparation for a practical demonstration can have serious consequences.

2.1.1 Case Study B

"I never saw anything like it," said student Diana S, who was in the chemistry lab when the blast occurred.

This second case study concerns an accident in a school chemistry laboratory. The local news media reported that:

A beaker exploded Friday after a chemistry experiment went awry at X High School, sending out a fireball that burned three students and a teacher.

The explosion occurred [as a] teacher was attempting to perform a common experiment that uses methanol and mineral salts to show how different metals produce different colors of flames.

She told the class, "This is why fireworks turn colors," and proceeded to pour material into a glass beaker…..the teacher [then] attempted to ignite methanol in some coffee cup-sized glass beakers. "When they failed to ignite, she began to add more methanol. … there was an explosion as the undetected flame ignited the fresh vapors," fire officials said.

It appears that the teacher in this instance had not fully appreciated the danger to both herself and to her students of what she was doing. Methanol burns with a flame that is hard to see, especially in a well-lit room. Evidently the accident was a result of her failure to recognize this, or to be aware that far safer methods for conducting flame tests exist.

2.2 Understanding chemical properties

It is essential to ensure safe working conditions in order to avoid accidents of the type outlined in Case Study B, but there are further reasons why safety should routinely be integrated into teaching, among them the opportunity that safety instruction provides to reinforce other aspects of science.

When a substance poses a risk to those handling it, this risk is a direct reflection of the substance's chemical or physical properties. Because the hazards that the substance presents are determined by its structure, as students learn about safety they can simultaneously be developing their knowledge of chemistry itself. The safety message and the chemical understanding reinforce each other.

2.2.2 Case Study C

Tuesday was just the second day of class at Y High School when teacher M began his science experiment, which had always been exciting but safe. Instead, a 5-gallon glass water cooler bottle shattered, sending shards of glass flying across the room and 22 students to local emergency rooms.

This was another incident illustrating the dangers of using methanol in other than well-controlled conditions. The reaction of local officials was perhaps surprising.

Officials quickly determined that the explosion was simply an unfortunate accident.

"Unfortunate" the event certainly was, and "accident", in the sense that it was unexpected, was a good description of what had happened. However the combination of these words into the phrase "unfortunate accident" seems to suggest that the incident could not have been foreseen, which would not appear to be the case.

"This was an approved demonstration experiment," High School principal D said. "What went wrong nobody can tell at this point."

A local University Professor provided a more detailed explanation of what had gone wrong:

“Methanol is …. used in a variety of experiments because it burns clean and, under normal circumstances, is quite controllable. The problem with methanol, a volatile liquid, is that it gives off vapors at a low temperature, around 50 degrees. It has a "wide flammability range" which means that there doesn't have to be a thick concentration of vapours for a fire to ignite.”

Notice in this explanation the degree to which the accident might have been anticipated through a knowledge of the properties of the chemical involved. Methanol “burns”; it is “volatile”, it generates significant quantities of vapour at modest temperatures and has a “wide flammability range”. If these properties had been known to the students and kept in mind by both them and their teacher, the “unfortunate accident” might have been avoided.

As one of the students in class subsequently is reported to have commented:

"And people ask me why I don't like chemistry."

while a parent commented more perceptively

"An accident isn't really an accident. It's someone else's mistake."

2.3 Long term appreciation of safety

Every substance that exists is a chemical. However, consumers are often impressed when a product contains "no chemical additives", or that "no chemical fertilizer was used in the production of this grain", since there is an increasing desire to avoid "chemicals" in food.

This illustrates the deep apprehension - and misapprehension - that exists amongst members of the public about chemicals. Quite reasonably they wish to avoid putting themselves or the environment in danger, but lack the basic knowledge required to make reasoned judgments about whether their actions may do this.

Many difficult environmental and ethical scientific issues exist on which there are wide differences of opinion among the public: genetic manipulation, the greenhouse effect and global warming, the enlargement of the ozone hole, the discovery of residues of contraceptives and agricultural fertilizers in drinking water, the widespread use of colourants in food and more.

Ideally, decisions about such matters would be taken by the population at large, not by scientists alone or (much worse!) just by politicians. However, without an adequate understanding of safety or, more broadly, science, people make decisions on the basis of gut feelings, or incomplete knowledge.

Within a few years of studying science at High School, students will find themselves with the power to influence decisions, as voters, or even the chance to put forward possible courses of action, as lawmakers. In order to assess realistically the hazards associated with a chemical, an understanding of safety and the ability to make a realistic judgment about the potential hazards of an operation or chemical are vital.

The failure to make justifiable assessments of risk is illustrated by the several chemicals that are discussed in Case Study D.

2.3.1 Case Study D

The Food Standards Agency (FSA) in the UK is a government-funded body responsible for ensuring the safety of all consumer foods.

In February 2005, the FSA became aware that a batch of chili powder used in the preparation of a range of foods had been contaminated with Sudan I. Sudan I, a bright red dye licensed for use in a variety of products but not, in most countries, in food, had apparently been illegally added by suppliers in the Indian subcontinent to a batch of raw chili powder to make it appear more appealing. More than 450 food products in the UK suspected of contamination were removed from shops within days but the problem quickly emerged in other countries as products that might have been contaminated before export were identified.

The rapid action taken by the FSA in the UK, and by similar bodies in other countries was understandable. The IARC had previously reported that Sudan I had been found to be carcinogenic in mice following its subcutaneous administration, producing tumors of the liver. It was thus judged by the FSA to be dangerous to health.

But was the action taken by the FSA a realistic and proportionate response to the dangers posed by Sudan I, or just one that the public would expect and approve of?

Although the IARC stated that Sudan I was carcinogenic by subcutaneous administration, it also reported that tests by oral administration in mice and rats were negative.

Food Standards Australia similarly indicated that the dye did not present an immediate or serious risk:

"There is ..... no evidence that [Sudan I dye] can cause harm in humans, particular at the low levels found in these foods."

In view of the very low level of any Sudan I residue and the fact that any contaminated food would have been swallowed rather than administered subcutaneously, it is reasonable to conclude that the real risk posed by the contamination was almost certainly negligible.

Despite this, there was a high level of concern among consumers in Europe. The public response to the withdrawal of food products was revealing. On 10th March an anonymous poster on Irishhealth.com wrote

"What worries me is what other dangerous additives are in food. If you look at the list of ingredients on some of the packaged foods, some of the items listed are barely pronounceable."

The implication that a chemical whose name one cannot articulate is somehow more dangerous than one whose name one can, is surely not a view that a scientist would have sympathy with.

Irishhealth.com reported that

".... many people contacting the authority .... wanted to know whether they could check the ingredients on packets of food for [Sudan I]. But as it should not be in food in the first place, it is obviously not listed. "

This sort of query from consumers reveals both a deep level of mistrust about "chemicals" in foods and a serious of understanding about how one might assess any dangers.

A further illustration of how difficult it is for the general public to know what chemicals are or are not safe is provided by the NTP (National Toxicology Program).

In its 11th RoC report, released on Jan 31, 2005, the NTP identified 2-amino-3,4-dimethylimidazo[4,5-f]quinoline and phenylimidazopyridine as potential carcinogens; both may be formed when meat or fish is grilled at a high temperature or barbecued. Sudan I is not listed by NTP as a carcinogen, but these chemicals produced by barbecuing are.

It is illogical, though perhaps understandable, that many people would be happy to continue to barbecue meat and fish, but at the same time would feel nervous about eating a commercial product contaminated with a dye which represents perhaps only a modest danger and is present in foods at levels so low as to be close to or below detectable limits.

This reluctance or inability to accurately assess the harm that a chemical might pose is deeply embedded, as a further example illustrates.

Acetaldehyde is classified by NTP as one that is reasonably anticipated to be a human carcinogen.

Should we therefore be trying to avoid all exposure to acetaldehyde? In fact, it would be extremely hard to do so: acetaldehyde is used as a flavoring agent and adjuvant. It is added to milk products, baked goods, fruit juices, candy, desserts, and soft drinks to impart orange, apple, and butter flavors. It is used in the manufacture of vinegar and yeast and as a fruit and fish preservative. It is found in trace amounts in all ripe fruits and may form in wine and other alcoholic beverages after exposure to air. It is found in leaf tobacco, tobacco smoke and automobile and diesel exhaust.

It is a product of alcohol fermentation and is a metabolic intermediate in higher plants. It is a volatile component of cotton leaves and blossoms. Acetaldehyde occurs in oak and tobacco leaves and is a natural component of apples, broccoli, coffee, grapefruit, grapes, lemons, mushrooms, onions, oranges, peaches, pears, pineapples, raspberries, and strawberries.

There are numerous other sources, including cheese, cooked chicken, rum, room deodorizers, marijuana, cigarette smoke, burning wood, forest fires, volcanoes, rosemary oil, mustard, and ambient air. It is clear that this is a ubiquitous chemical. Despite that, it is listed as a hazardous air pollutant by NESHAP and a potential occupational carcinogen.

This lengthy case study illustrates how difficult it is to assess potentially harmful chemicals and determine how one should react to their presence in the environment. Only in the easiest of cases, for example exposure to cigarette smoke, are the hazards well documented and means of avoidance simple to understand.

However, exposure to moderately harmful chemicals is very widespread, indeed it is virtually unavoidable, and the scientific training needed to make informed decisions regarding such exposure resides with only a small proportion of the population. If safety becomes more deeply embedded in science teaching we may be able to create a population more able to make the critical judgments about chemical exposure.

3. What are we doing wrong?

Science has a mixed public image. Scientists have been responsible for great advances in society, but for great threats too.

At school, science may have a "nerdy" image, and enthusiastic science teachers can try to raise its popularity by engaging in spectacular and flashy experiments, to create excitement about the subject. Such experiments are often memorable, perhaps in proportion to how dangerous they are, and may succeed in increasing interest in science.

Nevertheless, they are not without their disadvantages. From them, students may get a distorted picture of both science and safety. They may come to believe that the dangers in chemistry are readily observable and controlled: "See, the chemistry teacher gets this spectacular explosion right every time, she never blows her hand off". Conversely, they may come to believe that chemistry is the science of danger, full of hazardous and unpredictable materials.

Neither view is the whole truth, but much of the rather poor reputation that chemistry has can be traced back to this kind of unbalanced view of the threat that chemicals pose. Safety depends upon context: chlorofluorocarbons (CFCs) are inert at ground level, yet present a hazard in the stratosphere where they destroy ozone. By contrast, ozone itself is harmful to both animals and materials at ground level, yet life would be virtually impossible without its presence in the upper atmosphere. Some understanding of science is necessary to understand how such chemicals can be both safe and harmful.

4. How can we improve safety?

As the earlier case studies illustrate, one of the most important responsibilities of the teacher is to develop in students an understanding of safe practice.

With suitable instruction and encouragement students will work more safely in the laboratory; they will more readily comprehend the properties of substances if they understand that safety and chemical structure are linked; they will be able to make more reliable judgments about important scientific issues in the "outside world" if they have been well versed in safety matters; and they will be more likely to see the chemistry teacher's flash-bang experiments for what they are - demonstrations of the properties of exceptional chemicals, not a demonstration of how everyday chemicals can be expected to behave.

Improving students' understanding of safety so that they both learn effectively and work safely requires an attack on several fronts. While many of the suggestions below are straightforward, there will perhaps be some ideas for improving safety in the classroom you have not tried.

1. Safety is not optional, so cannot be open to negotiation between students and teacher.

More than in any other area, it is essential that safety rules be clear, unambiguous and rigorously enforced. The requirement to work safely should be as central to the course as the use of textbooks.

2. Students should be provided in advance with safety data where appropriate, but also encouraged to search for data on-line or in books so as to become familiar with sources of data, their structure, and the abstraction of relevant information from them.

Time required for initial instruction on how to search will be time well spent. However searching must be done with care - simply typing "Ethanol MSDS" into a search engine will generate hundreds of thousands of hits, but the data must be in a form that students can understand without additional help. Detailed MSDS data are difficult to interpret, so a short list of web sites that provide data in a suitably simplified form is helpful.

The HSci Safety web site [1] provides data on a number of common chemicals in a format that is readily interpretable, and suggestions for additional chemicals for inclusion on the site are welcome.

It is valuable to assess web sites before they, or particular pages from them, are recommended for use, otherwise the information that they provide can be counterproductive. For example, the otherwise very helpful site LabSafety.org reports that

"While many lab accidents involve methanol—an extremely flammable liquid also known as methyl chloride—........"

3. Safety should not be treated as an after-thought, tacked on at the end of the instructions for an experiment.

Whenever the risks presented by a chemical are being discussed, an attempt should be made to spell out the physical and chemical reasons *why* a chemical is dangerous, not just the fact that it is.

Diethyl ether presents a considerable fire and explosion risk. This should be explained by making it clear that the ether is very volatile (due to its low molecular weight and the comparatively low intermolecular forces in the liquid), that it forms a heavy vapour that can travel across benches and settle in sinks (molecular weight significantly higher than that of air) and that it burns very vigorously (formation of carbon dioxide and water from organic compounds is usually very exothermic). The linking of safety matters to properties should enhance student understanding of both, as well as encouraging them to think!

4. The health and safety hazards of all substances involved in a procedure should be researched and noted down by students before the experiment is begun.

If students have discovered for themselves that they will suffer burns if the chemical is spilled on the skin, the message seems to have more of an impact than if they are merely told about it. An occasional check on students' safety research before they start work will encourage them to do a good job.

5. When environmental issues can be introduced into a discussion, they should be treated in an unbiased fashion, neither emphasizing nor downplaying the risks.

Encourage students to interpret environmental problems in terms of the way the chemicals behave, not just the fact that chemicals can, under certain circumstances, be harmful.

For example, CFCs are stable and harmless at ground level, but harmful in the stratosphere and so have largely been phased out of use in refrigerators, deodorants, etc. It would be simple to explain that CFCs have been found to damage the upper atmosphere by destroying ozone, but it is surely better to explain why there is a problem.

What particular properties of a CFC are responsible for its classification as a pollutant? If CFCs are banned, can we estimate how many years will pass before they no longer present a hazard? The lifetime of CFCs in the atmosphere is very long; what feature of these compounds and their behaviour is responsible for this? When chemicals such as CFCs are banned, how can we judge whether alternative chemicals will be any better? Might the environmental impact of alternatives be different but perhaps just as harmful?

By tackling a topic in this way, the safety issues are integrated into a study of chemistry and the environment, making the whole exercise both more effective and more interesting.

6. Students must be encouraged to appreciate that environmental issues are almost always complex.

For example, DDT concentrates in body fat and has had a serious effect on the reproductive capabilities of wildlife near the top of the food chain in many parts of the world. Consequently it is now rarely used.

However, common replacements for DDT are inferior in terms of mosquito control, and it is legitimate to ask what level of suffering amongst humans and their livestock is permissible to obtain a given improvement in the welfare of surrounding wildlife. There is no easy answer to such a question, but students will gain much by being given the opportunity to consider it.

7. Students should be asked to take sides when debating issues of safety.

By doing so they will learn to appreciate the complex nature of environmental decision-making and be better able to make a reasoned judgment in the future.

8. Links between safety and ethical issues should be addressed.

Who is responsible if a hazardous chemical is dumped illegally in a water course, or if an industrial company allows toxic waste to contaminate its land? The answer is obvious, but not all pollution problems can be so easily laid at someone else's door. Who is responsible if a municipal water supply becomes contaminated with residues of contraceptive pills, as is now happening in many western countries? In some senses the risks presented by chemical contamination are only a small part of a story since most chemicals produced industrially are harmful only if used in inappropriate ways.

9. Everything is chemical – this should be made clear from the start of a course, as soon as students learn what a chemical is.

The belief that "chemical" fertilizers are harmful while "natural" fertilizers are safe reveals a gross misunderstanding of what the term "chemical" means. A blanket view of the safety of chemicals is neither necessary nor wise. The chemicals that are given "E numbers" when added to foods include many that are therapeutic, yet it is common to hear people arguing that the fewer E-numbers a food contains the better it must be. It is helpful if positive images of chemicals are presented, for example their use in recycling, to counteract the inevitable negative examples.

10. Where possible, the hazards that a chemical may pose should be related to its position on the Periodic Table and to the behaviour of those chemicals close to it on the Table.

Students learn almost as soon as they encounter the Periodic Table that all elements in group I produce corrosive hydroxides and that those in Group 8 are inert and therefore generally safe. The hazardous properties of chemicals can be considered alongside other properties, such as mass or degree of metallic properties. It is also often helpful for students to be asked to compare two substances, both chemically and in terms of the hazards they might present.

11. A standalone safety course should not be used to replace more traditional approaches unless there are strong arguments in its favour.

A course devoted entirely to safety is almost inevitably theoretical rather than practical, but the best way to learn about safety is by learning from a competent teacher in the laboratory. When a purpose-built safety course is offered, those teaching "standard" science courses may feel that safety has been adequately covered elsewhere and that they need give little further instruction, or just rely on showing a CD once a term.

12. Within a group of students the burden of finding out about safety should not fall on a just one.

It is tempting for a group of students to assign the task of researching safety issues to one of their number, while the others get on with the experimental side of the task. However, the experimentalists may then fail to appreciate the safety implications of what they are doing, or overtake the safety expert in the group and encounter a problem before the relevant safety information has been located.

13. Students should spell out, in written form, the health and safety implications of the experiment before they start work.

The analysis should explain *in their own words* how the students will minimize or eliminate relevant risks - a few printed pages of MSDS data should not be regarded as sufficient to demonstrate an understanding of the problems that might arise.

It is helpful to ask students to speculate about "what could go wrong?" Suppose the beaker of flammable liquid they are using is knocked onto the bench and breaks, spreading liquid across the bench; is there a source of ignition nearby? If a fire ensured, are there other chemicals on the bench or shelves above it that might also catch fire and perhaps lead to a major incident?

14. Approaches should be tailored to the needs of different groups of students.

Clearly a group of ten-year olds will need a different approach from a group of seventeen-year-olds, but so too will a group of chemists need an approach that is different from that required for a group whose interest is in geography or biology.

15. Both processes and properties should be discussed.

Runaway reactions are responsible for accidents in industrial laboratories and in university teaching laboratories each year. Discussing these reactions provides an excellent core topic around which the interplay between kinetics and thermodynamics can be discussed.

5. References

This section contains references to a small number of online sources of information on safety. The Internet is a somewhat less reliable source of data than the printed page, but is undoubtedly cheaper and generally more convenient. With care, therefore, in the choice of web sites, the web can provide an effective means of securing safety data for all the common chemicals used in the laboratory.

[1] The HSci database of chemical information for students provides data on a small but growing number of chemicals that are widely used in school and College laboratories. Suggestions for additions to the database are welcomed by the database owner and are normally dealt with rapidly. http://ptcl.chem.ox.ac.uk/~hmc/hsci/hsci_chemicals_list.html [June 1, 2005]

The Safety Database of the Physical and Theoretical Chemistry Laboratory at Oxford University contains a wide range of safety data, covering not just chemicals but reactivity and other risks, a chemical glossary, data regarding choice of protective gloves and similar information. http://ptcl.chem.ox.ac.uk/MSDS [June 1, 2005]

The Siri web site contains links to a large database, much of it provided by suppliers of chemicals. There are numerous further useful links. http://www2.siri.org/msds/index.php [June 1, 2005]

The Occupational Safety and Health Administration and its sister agency NIOSH provide extensive background data, and is a useful resource for those investigating policy rather than just the safety of specific chemicals. http://www.osha.gov/ [June 1, 2005]

The U.S. Environmental Protection Agency web site is a second source of general information about a wide range of environmental and safety issues. http://www.epa.gov/ [June 1, 2005]

The EPA and OSHA web sites are sufficiently complex that, if you intend to use them in class, it is wise to do some preliminary research so that you can readily direct students to useful information if they get lost!