Inherently Safer Design—a course for science and engineering students*

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Introduction

Until the Bhopal Gas Tragedy in 1984, there were few courses and few researchers in chemical process safety around the world. That tragedy shook everyone out of complacency: the public, media, legislators, judiciary, academics, NGOs (non-governmental organisations) and the process industry. Now there are more courses, more researchers, more research journals, more conferences and more legislation on process safety and loss prevention. The result, to quote Trevor Kletz,[1] is that 'the loss prevention movement has prevented many hundreds of deaths'. Considering that for each fatality, there are 2–3 serious or permanent injuries, many more minor injuries, together with trauma and economic loss, the value of loss prevention can be appreciated.

With interest in the field of loss prevention aroused, should chemical process industry (CPI) be content with minor improvements? No! Although most of the public accept that chemicals are essential to their way of life, they are at the same time looking to the CPI to get its safety act together—*fast*. Fortunately for the CPI, Trevor Kletz propounded the concept of Inherently Safer Design (ISD) over 2 decades ago—a concept which has been accepted very gradually by the CPI and other stakeholders. There have been several research papers, books and conferences on the topic.[2–7]

ISD has been defined as 'Any improvement in a layer of protection which is permanent and inseparable and not easily weakened or removed from the system'.[5] It has been divided into the following five categories:

- Intensification or minimization of the amount of hazardous material present at any given time, be it in a reactor, pipeline, transport vehicle or storage tank. For example, use of continuous tubular reactors instead of a large batch reactor.
- Substitution of a hazardous material by a less-hazardous or non-hazardous one. Replacement of flammable organic solvents by water is an example.
- Attenuation or toning down of the operating conditions of pressure, temperature, concentration, *etc*. For example, over several decades, the pressure in ammonia synthesis has come down from several hundred bar to about one hundred bar.
- Limitation of the effects of any hazard materializing by bunds, fence wall, judicious layout, siting away from habitation, *etc*.
- Simplification of the plant. Simpler plants are easier to design, fabricate, erect, operate, control and maintain.

Such inherent safety aspects do not require periodic testing, maintenance or replacement, as is the case with the

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add-on or engineered safety items. There will, however, be a continued need for engineered (or add-on) safety, since some activities are better done that way, and some activities will not be made as safe as is reasonably possible by ISD alone. The proportion of (and hence the cost and probability of failure of) add-on safety will nevertheless reduce as more people start to practise ISD.

Basically, ISD requires questioning in an unbiased and thorough manner all the steps from choosing a product, process to produce it, design and layout of equipment and control systems, operating conditions, transporting product to the market and its use by consumers. Inventories at each step must also be carefully considered since so much money is tied up in them, and they can cause significant damage and casualties due to fire, explosion and toxic release. The cases of Bhopal and Mexico City are still fresh in the memory.

The present author firmly believes that if ISD principles are followed along with process miniaturization as forcibly argued by Benson and Ponton[9] the CPI in 2020 will look a lot different and friendlier. Equipment sizes will be smaller due to higher efficiency and distributed production at the customer site. Operating conditions will be less severe due to the development of better catalysts and friendlier process routes, and inventories will be significantly smaller following the 'just-in-time' principle, to the extent the infrastructure can support it. All of this will reduce the capital cost and costs related to operation (less energy, personnel requirements), inventory size, maintenance, process upgrading, transport of raw material and products, environment protection and decommissioning of the plant at the end of its useful life.

The key to achieving all the above is spreading the word about ISD, practising it vigorously—one may even say ruthlessly—and publicizing the gains obtained (keeping in mind the inventor company's desire to maintain confidentiality to recover its expenditure and more). For any idea to spread, it has to be taught at the earliest, appropriate stage. In the case of ISD, the appropriate time is the first-degree course in science and engineering. I describe a one-semester course on ISD. For engineers and scientists to apply ISD principles, support from the organisation bosses is essential,[10] because ISD challenges the *status quo* in design and operation, and management need to be persuaded to consider doing things differently.

The concepts of ISD, as stated by Kletz and further elaborated by others, are so simple and common sense that they can be understood by anyone with a basic scientific knowledge. Hence our course will benefit those in the construction, automobile, metallurgical, aviation industries, *etc.*, until more focussed courses are developed in these areas.[8]

The ISD Course

The one-semester course consists of 3 lecture-hours per week for 12–14 weeks; the lectures can consist of three 1-hour lectures per week, or, as the present author prefers, two 1½-hour lectures per week.

The 'highly recommended book' for the course is that by Trevor Kletz.[2] Since there are no other ISD courses (this being the first course as far as is known) and the book was not really written as a standard textbook, it needs to be supplemented by other publications.[3–7]

Students need to be encouraged to study the various topics in advance of the lecture, since ISD attempts to change fundamental attitudes towards safety and current ideas on how process plants should be designed and run. Hence, reading in advance will better prepare students to understand the lectures and hopefully modify their thinking. Therefore, the instructor needs to give advance reading assignments on at least a weekly basis.

The students should already know the techniques of hazard identification, risk analysis, calculation of consequences, *etc.* †—topics covered in a normal Loss Prevention or Chemical Process Safety courses[11–14]. This will help them in determining the situation both before and after the ISD principles are applied.

For each topic mentioned below, it is necessary for the lecturer to give examples utilizing the related ISD methodology; such examples are quoted in the literature cited at the end of this article.

Topics covered in the ISD Course

Hazards in CPI

Knowing these is the first step to think of ways to avoid, minimize or contain them.

Selected major accidents

Discussion on these brings out the potential major plants have to cause disaster. It is preferable that students examine the case studies given by Lees[11] and present them in class. The instructor may supplement these with photographs and videos, as available. It is vital to point out how these accidents could have been avoided or effects minimized by using ISD principles. For example, at Bhopal there was no need to:

- use the process route that produced MIC (methyl isocyanate) as an intermediate
- store so much MIC when, even with the existing process, a different reactor design would have cut the inventory of MIC to a few kilograms in the reactor with no intermediate storage of many tonnes required[2]

Review of ISD methodologies

This should give an overview of ISD techniques and at what stage in the evolution of a plant these should be applied—actually, the earlier the better, starting at the lab process development stage, but these can be applied with advantage at just about any stage and even on the installed and operating plants. It has been well said about ISD techniques: 'Start early and never stop'.[5]

Attention should then be turned to specific ISD methods with available examples provided in each case. The hazard potential of pre- and post-ISD application should be analyzed in each case to justify the application and cost of ISD.

Intensification or minimization of hazardous substances

This should be done at every stage possible: in storage or warehouse; in process equipment such as reactors, distillation towers, heat exchangers, mixers, *etc.* and in transportation. Reduced amounts of hazardous substances reduce the possible consequences of any hazard such as fire, explosion, or toxic release.

Substitution of a more hazardous material by a less- or non-hazardous one

The consequences of any hazard materializing would be proportionately less. This requires serious thought at the process development stage as it becomes very expensive to substitute a hazardous substance by a less hazardous one at a later stage, when add-on safety features are the only way left. According to Trevor Kletz, the life-long cost of an add-on feature is twice its capital cost

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† If the students do not know these techniques, they need to be taught in 8–10 one-hour lectures before starting on ISD.

due to the need for testing, repairing and maintenance all through its life.

Attenuation or moderation of operating conditions

The pressure, temperature, concentration, *etc.* should be reduced as much as possible at every stage to reduce the consequences of any failures. At times, attenuation may run counter to intensification since reduced temperature or concentration lowers the reaction rate resulting in larger inventory in the reactor. Such situations should also be pointed out, so that ISD is used sensibly, not blindly as a panacea.

Limitation of the effects of failures

Siting plants away from habitation should be considered, as well as plant design and plant layout to minimise the effects of failures both on-site and off-site. Control of habitation or maintenance of a ‘green corridor’ around hazardous plants can limit the off-site effects.

Simplification of plants

Simpler plants are obviously easier to operate and so one should not attempt to do too many different operations in the same equipment—it involves too much piping, valves, bypass lines, *etc.* Wrong setting of valves, less than thorough cleaning after earlier usage, *etc.*, can result in problems. Simpler plants also cost less to fabricate, operate, maintain and control.

Other ISD techniques[2]

- design plants to be error-tolerant
- avoiding the domino effect
- making incorrect assembly difficult
- provide easy control of a process

Software safety

Computers have just about taken over the control of all major CPI, with software generally written by non-chemical engineers. Software errors can be significant, especially in new or one-of-a-kind software, and these must be thoroughly tested. Examples of disasters caused by software errors are available.[15,16]

Use of indices to rate ISD

DOW, Mond and PIIS (Prototype Index of Process Safety, Loughborough University) can be used to rate the effects of ISD techniques. Other indexing techniques may also be developed in due course as more experience is gained in ISD.

Life cycle approach

Consider all aspects from R&D, process development and design, plant erection and commissioning, operation, modifications, attention to upset conditions, maintenance and decommissioning after the plant has run its useful life, applying ISD principles at each stage.

R&D needs

The R&D in process safety has not kept pace with the need.[17] It is very important to emphasize this and point out areas in need of R&D. Depending upon availability of laboratory facilities and background of the students, some of these could be given as a semester project, under close supervision since students will not have much experience in laboratory safety.

Decision making regarding ISD usage

Why is ISD taking so long to be accepted? Answers to this might include: conflicts of ISD with environmental regulations, trade-offs between ISD and other techniques, etc. Also, warn the students that the applicability of ISD techniques should be thoroughly investigated lest they should create a different set of hazards.

Maintenance of Records[2,10]

Many decisions on process safety and application of ISD are taken based on sound principles, knowledge and experience, but the people making the decisions eventually move on. New hands might be tempted to alter the system by tinkering here and there, or in one big push. Accidents are likely to happen if reasons for decisions made years ago are not known. Hence, it is most important to record the reasons and calculations done for each decision and design. Before making any change, reasons for the existing design, operating conditions, *etc.*, must be known. This will avoid accidents and much grief later on. Students should therefore be asked to write in simple and understandable terms the changes they propose in any class exercise design using ISD concepts.

Since ISD is a relatively new field, it is not easy to offer a full course in it, and it is still less easy to examine student performance in it. The teacher will have to devise innovative ways to test a student’s grasp of the topics. Experts from nearby industries can be helpful in testing by proposing real problems to which the students may be asked to apply ISD techniques. Since there will not be one correct answer in most cases, grading of students’ responses will also have to be innovative. It should not mar a student’s interest in ISD for the rest of his/her life. That would arrest the progress of ISD more than the teaching of the course would advance it!

Recommended journals on chemical process safety

The Chemical Engineer, IChemE (UK)
Journal of Hazardous Materials, Elsevier
Journal of Loss Prevention in the Process Industry, Elsevier
Loss Prevention Bulletin, IChemE (UK)
Loss Prevention News, Loss Prevention Association of India
Process Safety and Environmental Protection, Trans IChemE, Part B
Process Safety Progress, AIChE

It is strongly recommended that the students should be taken on a tour of at least one safety-conscious large CPI about two-thirds of the way through the course. The chosen industry’s reactants, products, processes, operating conditions, annual production, customer location, *etc.*, should be discussed beforehand to the extent that the company’s commercial and technological confidentiality considerations allow. This would prepare the students to apply ISD principles after viewing the plant personally. Company personnel should be on hand to discuss the students’ recommendations on the use of ISD in their plant; both the company and the students will gain.

If students have not had a process safety or loss prevention course, then they first need to learn the following topics for hazard analysis. This will help them analyze the benefits and costs of applying ISD methodologies:

- HAZOP
- Dow and Mond Indices
- Fault-tree Analysis and Event-tree Analysis
- Pool Fire, Fire Ball and Explosions
- Gas Dispersion

Students need only simple models and examples since their aim is to compare the pre- and post- ISD systems.

Conclusions

Teaching of ISD will spread the message and give new insights to future designers. While this article has dealt with a one-semester course, the same has also been repackaged for practising engineers as a 3-day short course. The vast experience of these practising engineers will produce intense interaction and will be extremely helpful in further refinements of the full-semester course as well as in more committed practice of ISD.

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CONFERENCE

ADHOC - 99

The Seventh International Symposium on Dioxygen Activation and Homogeneous Catalytic Oxidation (ADHOC-99) was held at York, UK, from 19–23 July 1999. At the meeting, attended by both chemists and biochemists, progress was reported towards the ideal homogeneous oxidation catalyst—one with high selectivity, high stability, and low environmental cost.

Biochemists gave several presentations on the mode of action of soluble and membrane-bound methane monooxygenase, which catalyses the dioxygen oxidation of methane to methanol. Such biological oxidases, or microorganisms containing them, show excellent selectivity and are being used to produce a variety of chiral organic compounds of commercial values in the pharmaceutical and other industries.

Chemists reported on the production of several new homogeneous oxidation catalysts, e.g. soluble manganese complexes for olefin epoxidations; chelating diamine–palladium complexes for oxidation of olefins to ketones (a green version of the Wacker reaction); and soluble titanium-containing silicate cage compounds as analogues of the titanium-containing zeolite TS-1, already widely used for 'green' peroxide oxidation.

'Green' oxidation (minimum environmental cost) requires the use of hydrogen peroxide or air (or its reactive component dioxygen) as oxidant. The meeting demonstrated that highly selective catalysts for such 'green' homogeneous oxidation are being developed, but catalyst stability remains a problem.