INHERENTLY SAFER APPROACHES TO PLANT DESIGN

The benefits of an inherently safer approach and how this can be built into the design process

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Synopsis

The expansion of the chemical industries in the 1960 and 70's brought with it increasing concerns for safety. At that time pioneers in the field were working on several new approaches to address these safety concerns including risk assessment, HAZOP and inherent safety. Over the years the techniques of HAZOP and Risk Assessment have become a common and accepted part of the industry approach - but what of inherent safety?

This paper summarises the work to date on a HSE sponsored project being carried out in conjunction with industry to try to find some answers to this question and to help industry towards an inherently safer future.

It describes the concept of an "inherently safer approach" and its potential benefits from the view of the regulator and industry, and summarises the status of inherent safety and its application in industry today.

An approach is described showing how inherent safety can be addressed during the development and design phases of a project and highlighting some of the key issues to be considered. Examples are given of techniques being developed to help in this process.

Finally the paper highlights some of the more general issues that need to be addressed if inherent safety is to become an integral part of plant design and operation, and offers some practical steps that could be taken towards this goal.

Key Words

Safety, Inherent Safety, Inherently Safer, Plant Design, Process Safety, Process Intensification

1 THE HSE SPONSORED PILOT STUDY

The concept of "inherently safer" plant has been with us now for many years, but despite its clear potential safety and cost benefits, there have been few recognised examples of its application in chemical plant design. As a result the HSE decided to launch a pilot study to see how industry approached safety in the design of plant, and where and how "inherently safer" approaches fitted, or could be fitted, into this.

The pilot study, being undertaken by AEA Consultancy Services (SRD), is in 3 phases:

i a review of current approaches to plant design;

ii the development of a framework and tools to help industry address inherent safety in the design process;

iii the application of these tools to selected industrial processes to confirm the practicality and effectiveness of the tools and to provide results which could show the potential benefits of adopting an "inherently safer" approach in terms of reduced risks and other possible benefits such as reduced lifecycle costs.

Industry has been encouraged to participate in the project, to ensure that the relevant issues are addressed, to guide the development of tools and to provide "test beds" to prove the tools and provide anecdotal evidence of the potential benefits of an inherently safer approach. In particular a symposium was held at the end of 1992 bringing together representatives from industry, the HSE and AEA to discuss "inherent safety" and the progress on the project. It is intended to have other such discussions as the project progresses. The following sections summarise the work on the project to date, and briefly describe some of the tools that have been developed.

2 THE "INHERENTLY SAFER" CONCEPT AND ITS POTENTIAL BENEFITS

The safety (ie. safety, health, environmental and loss prevention) performance of any plant is a function of many factors but can be considered to be primarily dependent on the following aspects:

The quality of the people who design, operate, and maintain it;

The effectiveness of the management and management systems in design, operation, maintenance and incident response;

The effectiveness of engineered safety systems to control hazards;

The risk potential of the plant and the process being carried out.

A given level of safety performance can be achieved in different ways by apportioning different standards to each of these aspects. For example a high hazard plant can still be made "tolerably" safe by the use of (often expensive) safety systems combined with good personnel and management systems. One company may place an emphasis on its management systems, whereas another may rely more on engineered safeguards. The exercise becomes a balancing act between the risk potential of the plant, the risk reduction afforded by the various safety control and management efforts and the cost of these efforts. Traditional safety developments have focused on improvements in these areas of "add on" engineered controls and management and may have drawn attention away from the fundamental step of reducing the hazard or risk potential of the plant and process.

If the hazard potential of the plant can be reduced or even eliminated by careful selection of the process and good design of the plant, then the need for "add on" safety systems and detailed management controls is reduced. The plant can be said to be "inherently safer" because its safety performance is less reliant on "add on" engineered systems and management controls which can and do fail.

"Inherently safer" is just another way of expressing this idea of plant and processes that are by their nature less hazardous, either because they use inherently less dangerous materials, conditions or equipment, or because they are less prone to dangerous instabilities or runaway reactions. This approach has the advantage of providing a means to address safety, health, environmental and loss prevention issues in a strategic and integrated manner by dealing with the hazards at source, rather than perhaps retrospectively trying to find ways to live with them.

The classic definition of "inherent safety" is summed up by Trevor Kletz (Ref 1) as "What you don't have can't leak". This suggests an approach to plant design that minimises the amount of equipment - in fact the idea goes further to include plant where due to the materials involved or their small inventory the consequences of any leak would be minimised. Such an approach offers several advantages. Minimising the inherent hazard of the plant offers savings by reducing the need for expensive safety systems and instrumentation, easing the burden on personnel and procedures, and simplifying on-site and off-site emergency plans. In the extreme the hazards and risks may be so low that many of these controls may not be required at all.

In practice of course many of the processes we operate do require hazardous materials to be held sometimes in considerable quantities, or pose the threat of runaway reactions. The question to be asked therefore is "can we change the process or the equipment to make it inherently safer?". Kletz (Ref 2) sets out the routes by which we can achieve an inherently safer plant:

intensification -	reducing the hazardous inventories;
substitution -	substituting hazardous materials with less hazardous ones (but recognising that there could be some trade-offs here between plant safety and the wider product and lifecycle issues);
attenuation -	using the hazardous materials or processes in a way that limits their hazard potential eg. dissolved in a safe solvent, stored at low pressure or temperature; and
simplification -	making the plant and process simpler to design, build and operate hence less prone to equipment, control and human failings.

The goal of these routes is best summarised by the notion of a "friendly plant" (See Fig 1), which is tolerant of failures and , at the same time, less prone to failure. This combines the drive to minimise the hazard potential at source with the need to reduce the chance of the hazard being realised - by reducing complexity, minimising leak paths and adopting good ergonomic design. The model for a "friendly plant" as described in Figure 1 provides a means to visualise the "inherently safer" concept, so that it can be put to use. In essence all it does is to set out a definition of the concept that aids understanding and communication, and provides the basis for a systematic approach to inherent safety.

The definition also helps clarify the other benefits of the approach, for example reducing complexity reduces the need for instrumentation and operator supervision, and cuts the maintenance bills. Smaller inventories may mean smaller plant and storage facilities, hence possibly cheaper equipment costs and less land to put it on. Substitution for less harmful chemicals or processes could reduce the environmental impact of any wastes produced. Also inherently safer approaches encourage the systematic evaluation of the process and plant at the earliest stages of development and design, providing opportunities for greater process and cost optimisation. This becomes self-evident when you consider that upto 80% of the cost of a process plant can be committed by the time the conceptual flowsheet has been drawn up (Ref 3).

The increasing focus on environmental protection may prove to be a significant driving force to seek inherently safer approaches to design in a more systematic way, as such an approach offers the greatest opportunities to select and improve the basic process so that its environmental impact can be minimised. Also the deliberate pursuit of inherently safer plant could also help improve an organisation's public image and show its commitment to safety and the environment. Such approaches are sure to find favour with the regulators, where prevention is seen as better than cure, and with planning authorities striving to balance development with public concerns for safety. However we may note in passing that an inherently safer process may not necessarily be more environmentally friendly in the context of the full product lifecycle, and this may be an additional factor that has to be considered.

Given that these ideas and the potential benefits they offer have been widely publicised and accepted, at least in principle, for many years, the next stage of the project was to see how these were being incorporated into the design process.

3 THE CURRENT STATE OF PLAY

A search of published literature and interviews with a selection of chemical and nuclear companies were carried out to see how safety is being addressed in the design process, and if or where "inherently safer" approaches were included.

The results showed that "inherent safety" or its concepts only appeared in a few of the design safety studies and practices. Many safety studies only started at the detailed design stage when the opportunities to change the process had passed, reflecting an approach to safety reliant on control rather than elimination or prevention. Some companies appeared to foster a general culture that encouraged designers and chemists to seek "safety by design", but the general lack of awareness of the principles of inherent safety, combined with the more noticeable approach of "identify and control" probably means that many opportunities to adopt an inherently safer design are being overlooked.

Awareness of the "inherently safer" concepts as put forward by Kletz appeared to be limited to safety specialists, and not widely known amongst senior managers or the designers and chemists who have the greatest opportunity to use them. Some safety specialists had experienced problems in trying to introduce inherent safety into the design activity. It may be that the reason HAZOPS and QRA have been adopted is because they are not just a concept but also an activity or procedure that can relatively easily be carried out, costed, resourced and planned. If so, inherent safety needs a tangible tool or activity on which the concept can be carried, and the methods and tools outlined in the next section could be one way of providing this.

The overall impression was that safety is often only addressed late in the design stages eg. HAZOPs on P&IDs, and that any earlier studies tend to focus on hazard identification and control rather than trying to find alternatives to eliminate or reduce the source of the hazard. Furthermore the concepts of "Inherent Safety" are not widely known and are rarely applied in a conscious or systematic manner in the process development and design phases. Indeed a study of much of the technical and other literature produced by regulators, industry, commerce, and technical bodies shows that it is rarely written in a way which facilitates inherently safer approaches. As a result examples of inherently safe processes have probably arisen from other pressures such as economics or unsatisfactory safety performance in the past.

The way forward therefore requires the raising of awareness of the inherently safer issues and potential benefits, and the development of practical measures that can help companies address these issues when designing plant.

4 A FRAMEWORK TO ADDRESS INHERENT SAFETY IN THE DESIGN PROCESS

Safety is a key factor in the design of any plant or process, but this must be balanced against many other factors such as economics, practicality, technology, time, markets etc. To be successful it is necessary to integrate all these considerations at all stages of the project, from initial conception to completion. "Inherent safety" therefore needs to be integrated into the overall project and addressed alongside other objectives and constraints.

This requirement has been addressed on the project by providing a framework that enables the basis of the project / process / plant to be challenged in a systematic way at each of the key steps in the projects lifecycle. This framework promotes the identification of alternatives and allows these to be evaluated in terms of their inherent safety, cost and feasibility. The key steps to be considered are shown in Figure 2.

This approach confirms that most decisions affecting the inherent safety (and cost) of the plant have been taken by the time the conceptual design has been completed. Our project has therefore concentrated its efforts at developing means to address safety at these early stages, namely:

Initial product specification

Synthesis route selection

Chemical flowsheet development

Process conceptual design

There will of course still be many opportunities to improve safety at the detailed design stages and beyond, but these are unlikely to make such dramatic improvements in the basic risk characteristics of the plant. The detailed design stage does however tend to be the time in the project when careful attention to the aspects of people / plant interactions can help create a friendlier plant in terms of ease of operation and maintenance, leading to a reduction in the likelihood of things going wrong. These issues can be addressed by conventional studies such as the classic HAZOP, "human factor" studies and by providing guidance on good practice.

5 SOME IDEAS FOR "INHERENT SAFETY" TOOLS

Tools have been developed for each of the 4 stages highlighted in the assessment framework. Each tool has been tailored to help chemists and engineers address the specific issues relevant to that stage of the project. This section describes the tools being developed as part of the project.

The tools fall into 4 broad categories:

Structured "brainstorm" techniques to identify alternatives prior to flowsheet development

More rigid, HAZOP style, techniques to challenge flowsheets and process diagrams

"Prompt" checklists to address aspects of conceptual plant layout

Safety indices to "measure" the degree of inherent safety of a proposed process

The first three of these are aimed at identifying alternatives and evaluating these in a qualitative way to see which may be worthy of detailed consideration. Tools in the last category are intended to provide a more quantitative measure of the likely safety of the plant or process to assist in the screening of options.

The tools being developed are briefly described below.

5.1 Initial Product Specification

This tool is intended to bring together what are generally fairly separate groups within a company, the sales and marketing people, the development chemists and designers to see if there are alternative means to achieve the same sales objectives, but in an (inherently) safer way.

The process could involve the following stages depending on the type of product and the market situation:

i Challenging the product need

> This uses critical examination techniques, and consideration of underlying needs to see if there are alternative products or means of product delivery eg. bug repellant vs bug killer, granules or spray vs. aerosol, water based paint vs solvent based paint.

ii Challenging the means to provide that need

This uses a combination of searches of current processes and literature together with some brainstorming to see if there are alternative means to manufacture the product.

iii Screening of the alternatives

A simple screening process is needed to select and rank the most promising options. It is important that this takes account of the safety, practicality and economic and technical feasibility of the option at all stages in its life cycle. The screening process proposed considers the product lifecycle stages as outlined in ISO 9000 (see Figure 3) and at each stage notes any significant benefits or drawbacks. The resulting information, though judgemental in nature, should provide a systematic and holistic basis for selection.

5.2 Synthesis Route Selection

The objective at this stage is to see if there are any alternative synthesis routes, including different starting points, building blocks, assembly methods, carrier / delivery systems or processing conditions and mechanisms. These can then be evaluated in terms of their safety and feasibility.

Issues that can be covered include:

the use of natural vs recycled vs synthetic materials

retro-synthesis analysis

use of bio-synthesis or electro synthesis

use of different pressures or temperatures or solvents

use of novel separation techniques - ultrasonics, reverse osmosis etc.

assembly in a different state - solid, liquid or vapour

use of different solvents or other carrier agents (especially important in pharmaceuticals and agrochemicals)

Screening of the options involves considering the hazardous properties of the materials and intermediates involved, and of the reactions between these.
One important aspect is the potential for runaway and exothermic reaction. Simple energy approaches such as those proposed by Vilchez and Casal (Ref 4) could be used for initial screening.

5.3 Chemical Flowsheet Development

The chemical flowsheet sets down the reaction stages and the conditions under which these are to occur. It forms the bridge between the laboratory scale and the industrial process, and is often developed alongside pilot plant trials.

The objectives of safety studies at this stage are to understand the hazards of the process and to seek means to eliminate or control these. Rather than concentrating on engineered safeguards and control systems the inherently safer approach is to find ways to modify the reaction stages or conditions to eliminate or reduce the risk from these hazards. One way of approaching this is to carry out a HAZOP style study involving the development chemists, process engineers and safety experts which looks at each stage in the reaction scheme and uses a list of guidewords to prompt discussion of alternatives.

The guidewords could be split into 2 categories: those that challenge the materials such as the feedstocks, additives, solvents etc; and those that challenge the conditions under which these materials are added, and the condition under which the reactions take place such as the temperature, pressure, concentration, mixing, catalyst, physical / chemical form.

The study would identify alternatives to the proposed scheme and then evaluate these in terms of their contribution to safety and their feasibility. Giving each alternative a safety score of +, 0, or - relative to the original scheme may provide a simple way of screening to pick out the better options.

5.4 Process Conceptual Design

The conceptual design takes the chemical flowsheet and turns it into a series of unit operations that allow the process to be operated at the required industrial scale. It is at this stage that process engineers take over from the chemists, establishing the materials and energy balances, deciding the operational and control basis of the process (ie. batch or continuous, manual or automatic) and selecting the main unit operations and the type of plant and equipment to be used. The decisions made during this stage will determine the majority of the final costs and the operability and reliability of the plant and therefore they need to be considered carefully. It is very easy at this stage to simply follow what was done last time, or to select equipment without considering if it is really necessary, or whether their are more effective means to achieve that function.

To address these issues a method is being developed as part of the project to challenge the functionality and sequence of unit operations with the overall aim of finding alternatives that can optimise the design and make the plant inherently safer. The approach involves:

i breaking the process down into its basic building blocks (unit operations) and defining their basic function.

ii applying a list of guidewords to each block in turn to prompt ideas on possible alternative ways to achieve the same function.

iii applying a second set of guidewords to each block to see if changes to the timing, sequence and physical or chemical conditions can improve the process and its inherent safety.

iv evaluating the alternatives identified in terms of their safety benefit and feasibility.

The same process could also be applied to an existing plant which is about to be modified to help focus attention on the fundamental safety issues and steer the modification towards making the process inherently safer.

5.5 An Inherently Safer Index

All the tools described above are being developed to help those involved with the design to identify and evaluate specific opportunities to make the plant inherently safer. However it may also be useful to take an overview of the "inherent safetyness" of the plant, to target improvements or to compare performance with previous plants or other "options on the table". One way of achieving this would be to have an index which indicated the "degree" of inherent safety of a plant. An idea we are looking at on this project is to develop a numerical index which can be quickly applied at the concept design stage and scores the process on the following factors - a so-called "plant friendliness index":

the hazardous properties of the materials used and produced

the inventories of these materials in the plant

the conditions under which these materials are held

the degree of complexity of the process operations

the degree of complexity of the process control regime

The index can be targeted to look at conventional major hazard issues relating to the safety of people on and around the plant or to look at the environmental aspects of routine and accidental discharges. There are complex issues here, but early signs are encouraging.

6 CREATING AN ENVIRONMENT FOR INHERENTLY SAFER APPROACHES

It is important to realise that "inherent safety" is nothing new and is simply a phrase to describe an approach that exists in the minds of many scientists and engineers. The advantage of highlighting this approach and the benefits it can bring is that it can reach a wider audience, and lead to the concept being applied in a more conscious and systematic way. However such an approach is unlikely to be adopted merely through raising management awareness. If inherently safer approaches are to be adopted in the design of plant then the right working environment must be created. Managers will need to encourage and expect such issues to be addressed, designers and chemists need to be made aware of the concepts and how to apply them, senior managers will need to show commitment to this new way of working and support increased effort at the early stages of process development, and equally importantly the regulator must play their part in this process of education, support and encouragement.

Many of these issues were discussed at the 1992 symposium referred to above, and are summarised below:

6.1 Inherent Safety, Costs and Operability

Adopting an inherently safer approach gives good opportunities to reduce both capital and overall lifecycle costs (eg. operation, modification, decommissioning) by reducing the size and complexity of the plant and the need for "add on" safety systems that are expensive to install and maintain. This in turn can also improve and streamline the operability of the plant.

This potential for cost savings and greater operability ought to be a key attraction for companies, but this needs to be supported by some hard evidence if companies are to be persuaded. Perhaps companies could look to see where their plants have adopted "inherently safer" designs and compare the capital and running costs of these with conventional or previous plant. Such studies could make very interesting reading in engineering and management magazines and could be a powerful tool in highlighting inherently safer issues.

6.2 The Need for Safety to be Considered Early in Design

The real benefits of adopting an inherently safer approach can only be achieved if safety is considered alongside other objectives at the very earliest stages of development and design, and even as far back as deciding what product to make, or what process to carry out. It is these early strategic decisions that influence the final process and plant, and where the greatest changes can be made without incurring significant additional costs.

This could be achieved by incorporating the "inherently safer" concepts into design and development procedures, but would also benefit from other initiatives such as: in-house champions to carry the message into the design teams and other sections such as sales and marketing; having in-house "inherent safety" engineers or specialists to assist others and keep abreast of developments; training chemists and engineers to think in terms of inherent safety. The HSE can also play a role by taking a more active interest in plant safety at the design stage by asking how the plant has been made inherently safer, and by structuring its own guidance in inherently safer terms.

6.3 Awareness of the "Inherently Safer" Concept and its Application

For inherent safety to succeed its message must reach beyond the safety specialists to those who have the power to promote or use it effectively. This applies at all levels from senior managers to the draughtsmen on the drawing boards, although the information and its style of presentation will be different for the various types of people. Such issues should structure the method and content of proposals to those with strategic and executive decision making powers

The professional institutions and industry interest groups should use their influence to ensure that this education starts at the very beginning of vocational training in the engineering and industrial chemistry courses, and continues throughout a developing career.

Articles in leading management and design magazines combined with awareness / training aids, workshops and courses can help spread the message to those in industry. A competition for the best application of inherently safer design, or for the best overall contribution to inherent safety could provide a stimulating challenge.

6.4 Project Issues

Any project will have the potential for conflict between the desire to seek improvements and innovate and the need to bring the project in on time and cost with the minimum risk to a successful outcome. As a result many useful ideas may be rejected and lost either because they were considered a technical or financial risk, or because it was too late to change the design. One way of capturing these ideas is to appoint someone on the team to think about the "plant after next", so that good ideas can be followed up. Companies could think about placing a sort of "research levy" on projects to pay for R&D to develop and test some of these ideas that may benefit many future plants. Perhaps companies with similar problems could share in these ventures to spread the cost and maximise the application of the benefits.

The relationship between the client and any design contractors or consultants also influences the ability to make the design inherently safer. The design contractor or consultant needs to be aware of the "inherently safer" concepts and practices, and be committed to implementing these. The relationship and contractual arrangements should encourage innovation and interaction between specialists from all sides, exploiting the synergies that can be gained.

The licensors of plant and processes should be encouraged to be more flexible, balancing the need to retain the integrity of the product and route with proposals that could significantly improve the operation and safety of the process.

7 INDUSTRIAL TRIALS

The next stage of the project is to apply the developing tools to real situations in industry to focus their development and to seek anecdotal evidence of the potential benefits of adopting an inherently safer approach. The results of these trials should be available for the presentation of the paper.

8 SUMMARY

The concept of inherent safety as presented here is not new to safety specialists, but the chemical industry has made little practical use of the concept in the plants which have been designed since Kletz first started promulgating the concept in the 1970's. However by expanding the concept into a practical assessment tool, it can provide a route for the systematic development of processes and plant that are cheaper to build and operate, more tolerant of failures, less prone to failures and have lower consequences were failures to occur. It is hoped that this project can play a part in raising awareness in such approaches, and providing some ideas for tools to help designers and chemists address inherent safety in their work.

Inherently safer approaches to product and plant specification and design can provide the focus for strategic and fundamental improvement that will enable companies to maintain their competitive edge, and meet the increasing requirements of the current business, political and social climate to find more economic and safer means to satisfy market demands.

References

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FIGURE 1 - The Friendly Plant Concept

THE FRIENDLY PLANT CONCEPT - A RISK BASED APPROACH	
CONSEQUENCE REDUCTION	
FRIENDLY PLANT Tolerant of People or Equipment Failings	Classical Inherently Safer Plant Less Hazardous: * processes * materials * conditions and lower inventories
ALTERNATIVE - UNFRIENDLY PLANT "High Consequence" Plant	Needs Extra: * hardware * control systems * engineered safeguards ....to control hazards, leading to a complex (unfriendly) plant
FREQUENCY REDUCTION	
FRIENDLY PLANT Less Prone to People or Equipment Failings	Simpler Plant Simpler to: * design * build * operate * maintain
ALTERNATIVE - UNFRIENDLY PLANT Prone to Failings	Complex Plant Needs Extra: * hardware * control systems * engineered safeguards ....to prevent or control failings, leading to a complex (unfriendly) plant, and extra: * manpower * training * procedures * management controls ....to make plant operable

FIGURE 2 - The Steps to Plant Design

Decision Point	Key Questions/Decisions	Information Used
Initial Specification	What Product What Throughput	Market Research R&D New Product ideas
Process Synthesis Route	How to make the product What route What reactions, materials starting point	R&D Chemists research Known synthesis routes and techniques
Chemical Flowsheet	Flowrates, Conversion Factors, and Basic Unit Operation Selection, Temperatures, Pressures, solvents and catalyst selection	Process synthesis route Lab and pilot scale trials Knowledge of existing processes
Process Flowsheet	Batch vs Continuous operation Unit operation selection Control/operation philosophy	Information above plus process engineering design principles and experience
Process Conceptual Design	Equipment selection and sizing Inventory of process Single vs Multiple Trains Utility requirements Overdesign/Flexibility Recycles and Buffer capacities Instrumentation and Control Location/Siting of plant Preliminary plant layout Materials of construction	As above plus equipment suppliers data, raw materials data, Company design procedures and requirements
Process Detailed Design	Detailed specification based on concept design	Process conceptual design and codes/standards and procedures. Experience on past projects/designs

FIGURE 3 - Product "Lifecycle" (after ISO 9004)