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Reducing Physical Hazards: Encouraging Inherently Safer Production

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17.1
Introduction

Physical hazards differ from hazards related to the toxicity of chemicals and materials in a number of ways. Their origin is the *sudden and accidental release of chemicals and/or energy* – that is, chemical accidents, explosions, and spills – as distinct from the expected products, by-products, or gradual pollution associated with chemical production and use. The chemicals or materials are not always inherently toxic. For example, flour or olive oil can be explosive in an industrial operation if the particles or mist, respectively, are fine enough such that a spark leads to an ignition. Therefore, not only are the inherent characteristics of materials relevant, but also the processes associated with their production, use, or storage (for example, grain elevator explosions come to mind). More than substituting starting or feedstock materials – or making a different chemical – may be needed to prevent untoward events. Hence the design of both inherently safer materials and production systems must be addressed.

17.2
Factors Affecting the Safety of a Production System [1]

Factors that affect the safety of a production system include (1) the scale of production; (2) the quantity of hazardous chemicals involved; (3) the hazardousness of the chemicals involved; (4) batch versus continuous processing; (5) the presence of pressure or temperature extremes; (6) storage of intermediates versus closed loop processing; and (7) multi-stream versus single-stream plants. These factors are discussed briefly below .

17.2.1
The Scale of Production

Chemical production is typically characterized by economies of scale. Based on a generalized formula for the chemical industry, a doubling of plant capacity increases

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the capital cost by only about 60%. However, larger scale plants require a larger inventory of chemicals, which tends to increase the hazard potential of the plant. Therefore, from a safety standpoint, the optimal scale of production may involve smaller plants because chemical releases, although sometimes more frequent, would be smaller and easier to control.

17.2.2
The Quantity of Hazardous Chemicals Involved

The amount of hazardous chemicals on-site can be reduced by methods other than altering the scale of production. For example, the amount of hazardous material stored on-site can often be significantly reduced, and if not, the hazardous materials can be stored in many small containers in separate facilities rather than in a single container. Therefore, if a container fails, the size and catastrophic potential of the release are much reduced. In addition, the amount of material needed in the production process can be reduced by using specially designed equipment (such as Higee columns, which replace conventional distillation columns).

17.2.3
The Hazardousness of the Chemicals Involved

An obvious method for increasing the inherent safety of a production process is to substitute safer chemicals for more hazardous chemicals wherever possible. For example, flammable chemicals might be replaced by nonflammable chemicals; explosive chemicals might be replaced by less reactive chemicals; and highly toxic chemicals might be replaced by less toxic chemicals.

17.2.4
Batch Versus Continuous Processing

Batch processing involves loading feedstock chemicals into a process vessel, closing it, and reacting the vessel's contents to the desired final product. At this point, the vessel is emptied, and the entire process is repeated. Continuous processing, as the term implies, involves feeding raw materials to a reactor continuously and yields a continuous stream of desired reaction product.

Continuous processing is generally inherently safer than batch processing because smaller amounts of hazardous substances are present at any one time and because of the automated nature of the process. However, there may be size considerations that need to be taken into account regarding continuous processing. Connecting and disconnecting continuous processes may be especially hazardous (and this hazard will depend on the size of the processing vessel). On the other hand, utilizing smaller processing volumes may lead to smaller hazards per connecting/disconnecting event, but may involve a larger number of events, the sum of which may represent a larger total risk. A certain scale of production is normally required to make continuous processing feasible. For that reason, continuous production is sometimes considered to be more hazardous than batch processing. However, it is the scale of production which creates the hazard, not the mode of production *per se*. In many cases, techniques exist to adapt continuous processing to smaller volume production. However, in some cases, for example in some polymerization processes, batch processes are necessary.

17.2.5
The Presence of High Pressures or Temperatures

High (or low) pressure and high (or low) temperature storage and processing of hazardous chemicals is much riskier than the storage and processing of hazardous chemicals at ambient pressures and temperatures. High pressures and temperatures place storage and process equipment closer to the failure point and thus make them more susceptible to an accidental release. In addition, accidental releases from high-pressure vessels have a much higher rate of release than do comparable releases from near atmospheric-pressure units. Low temperatures may make materials brittle, and low pressures may provide significant pressure differentials which would allow the entrance of air into reactant vessels. The advantages of high pressures and temperatures in reactant vessels or pipes are that smaller volume equipment is required when the chemicals are under pressure and that, for many chemical reactions, the conversion of the reactants into desired products is facilitated, or the rates are increased, under high pressure and temperature. However, in some cases, this latter advantage can be overcome by using catalysts under ambient conditions to increase the rate of reaction to a level comparable to that achieved under high pressure and temperature – while at the same time increasing the inherent safety of the process.

17.2.6
Storage of Intermediates versus Closed-Loop Processing

Closed-loop processing involves having intermediate chemical substances formed in the conversion process (from feedstock chemicals to the desired final product) recycled back into the process stream until they react to form more of the final product. Both production economics and safety generally favor closed-loop processing when such technology is available because the intermediate chemicals are completely transformed into valuable final product instead of remaining as an undesirable and problematic hazardous chemical by-product. Because the research and development required are expensive, a closed-loop processing technology, in many cases, does not exist. However, where the impetus to change has been strong (such as in the production of carbaryl pesticides after the Bhopal tragedy), spectacular advances in inherently safer closed loop processing have been achieved.

17.2.7
Multi-Stream Versus Single-Stream Plants

In order to enhance production flexibility and to take advantage of different feedstock pricing patterns, chemical plants in some productive segments or product lines are designed to use a variety of alternative process inputs to produce a variety of products. Although economically attractive in a narrow production sense, such multi-stream plants increase the interactive complexity of the production process and thereby enhance the potential for system accidents. It is inherently safer to build simpler, single-stream plants dedicated to producing one product.

17.3
Chemical Safety and Accident Prevention: Inherent Safety and Inherently Safer Production

Although the concept of inherent safety is endorsed by the American Institute of Chemical Engineers, it is not in widespread practical use in US industry. When chemical engineers discuss the "root causes" of chemical accidents, they usually mean faulty equipment, pipes, vessels, and pressure valves. These really are "secondary" causes of accidents, and addressing them (e.g., through the use of stronger vessels and piping able to sustain higher pressures, neutralizing baths, automatic shut-off devices, and the like) constitutes "secondary" prevention. This bias in the chemical engineering profession has been one of the reasons why progress in eliminating chemical accidents has been relatively slow. *Primary* accident prevention, on the other hand, involves a fundamental redesign of the production process, with an emphasis on inherently safer chemicals and technology.

Inherent safety is an approach to chemical accident prevention that differs fundamentally from secondary accident prevention and accident mitigation [1–9]. Sometimes also referred to as "primary prevention" [1–3], inherent safety relies on the development and deployment of technologies that prevent the possibility of a chemical accident1). By comparison, "secondary prevention" reduces the probability of a chemical accident2), and "mitigation" and emergency responses seek to reduce

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1) The author is cognizant of the conventional wisdom that no technology is entirely safe, and that it might be more accurate to describe various technologies as saf*er*. However, some technologies are in fact absolutely safe along certain dimensions. For example, some chemicals are not flammable, or explosive, or toxic. Some reactions carried out under atmospheric pressure simply will not release their by-products in a violent way. Hence inherent safety is, in some sense, an ideal analogous to pollution prevention. Just as some might argue that pollution prevention can never be 100% achieved, purists may argue that technologies can only be made inherently safer, not safe. Articulating the ideal, however, makes an important point: dramatic, not marginal, changes are required to achieve both. Like pollution prevention, the term "inherently safe" focuses attention on the proper target.

2) In the accident prevention literature in the traditional chemical engineering journals, much attention is given to the concept of the "root cause" of accidents. Enquiry into root causes has stimulated mostly secondary prevention by attempting to make production technology more "fail-safe," that is, stronger vessels and piping able to sustain higher pressures, neutralizing baths, and automatic shut-off devices. A different tradition of analyzing accidents comes from tort and compensation law, where the "but-for" test is used to apportion responsibility between faulty technology and alleged careless workers. If the technology is not "fool-proof," that is, it is not impossible for a human to initiate an event leading to an accident, then the firm is held at least partially liable – because "but for faulty design, the accident would not have occurred." Primary prevention promotes "fool-proof." rather than "fail-safe" technology. Another formulation is "error tolerant" [10].

the seriousness of injuries, property damage, and environmental damage resulting from chemical accidents. Most chemical safety efforts to date have concentrated on secondary prevention and accident mitigation. Some reductions in inventory of hazardous materials, although heralded as primary prevention, may simply shift the locus of risk and increase the probability of transport accidents.

Secondary prevention and mitigation, by themselves, are unable to eliminate the risk of serious or catastrophic chemical accidents, although improved process safety management can reduce their probability and severity. Most chemical production involves transformation processes, which are inherently complex and tightly coupled. "Normal accidents" are an unavoidable risk of systems with these characteristics [11]. However, the risk of serious, or catastrophic, consequences need not be. Specific industries use many different processes. In many cases, alternative chemical processes exist which completely or almost completely eliminate the use of highly toxic, volatile, or flammable chemicals [12].

Inherent safety is similar in concept to pollution prevention or cleaner production. Both attempt to prevent the possibility of harm – from accidents or pollution – by eliminating the problem at its source. Both typically involve primary prevention that encourages fundamental changes in production technology: substitution of inputs, process redesign and re-engineering, and/or final product reformulation[3]. Examples discussed in the previous section include changing from a batch process using large amounts of explosive or toxic intermediates to a continuous flow process where the intermediates exist in very small amounts for very short periods of time.

Secondary prevention and mitigation are similar in concept to pollution control and remediation measures, respectively, in that each involves only minimal change to the core production system. In particular, secondary accident prevention focuses on improving the structural integrity of production vessels and piping, neutralizing escaped gases and liquids, and shut-off devices rather than changing the basic production methods. When plants expand beyond the capacity that they were initially designed for, secondary prevention capacities may be exceeded. Sometimes, overconfidence in these added-on safety measures may invite an expansion of production capacity. Accidents, of course, may also disable secondary safety technology, leading to runaway chemical reactions.

The superiority of pollution prevention and cleaner production as tools of environmental policy has been recognized for more than two decades in both Europe and North America [13,14]. International meetings of the Cleaner Production Roundtables and the Pollution Prevention Roundtables are held annually in Europe and North America, respectively. The United Nations Environment Programme has spearheaded an aggressive cleaner production program [13]. The US Environmental Protection Agency (EPA) has established a hierarchy of policy choices, with pollution prevention given the highest priority over reuse or recycling, treatment, or disposal [15]. In 1990, the US Congress codified, as national environmental policy, a

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[3] Although inherent safety and pollution prevention are similar in concept, there are practical differences between the two that have, so far, made the adoption of inherent safety measures less attractive to industry than pollution prevention/cleaner production.

preference for pollution prevention over pollution control, when it passed the Pollution Prevention Act. The EU supports its Directive on Integrated Pollution Prevention and Control (IPPC) by funding research in Seville, Spain, for the identification of Best Available Techniques (BAT).

In 1982, the European Union adopted the famous EU Directive (82/501/EC) on the Major Accident Hazards of Certain Industrial Activities, the so-called "Seveso Directive." It requires Member States to ensure that all manufacturers prove to a "competent authority" that major hazards have been identified in their industrial activities, that appropriate safety measures – including emergency plans – have been adopted, and that information, training, and safety equipment have been provided to on-site employees [16]. A second Seveso Directive (96/82/EC) came into effect in February 1997. Seveso II strengthens the original provisions and coverage of accident prevention activities, and also broadens the types of installations which must comply. Particularly worthy of note is the mention of inherent safety as a preferred approach to preventing chemical accidents in the accompanying guidance document for the preparation of the safety report required by the revised Directive [17].

Finally, a discussion of inherent safety (or cleaner production) would be incomplete without noting the importance of the stage of the production process where inherent safety is implemented. Production systems can be thought of a being comprised of at least four stages, which are found in each product line or productive segment in complex, multi-product line operations (Figure 17.1). The distinction between primary, secondary, and ancillary manufacturing and production processes – and also final products – is an important one for the identification of inherent safety opportunities. It also helps to explain why the receptivity to the adoption of inherent safety technology might be different for firms that (1) are already in existence and do not contemplate change, (2) are contemplating changes or contraction/expansion of capacity (what might be called "operations in transition"), or (3) are introducing new facilities or operations .

An illustrative example is offered in the context of casting and electroplating metal screws. The primary process is the casting of the screw (both toxic fumes and dangers from workers coming in contact with molten metals are recognized hazards). The secondary process is electroplating (this too presents both toxic and corrosive hazards). The ancillary process is cleaning or degreasing the screw using organic solvents (which can be both toxic and flammable). The screw itself may have sharp edges and present an occupational hazard. If the firm focuses on the ancillary process, it might be relatively easy for it to search for and find an alternative, nonpolluting, nonflammable cleaning process. Technological innovation would not likely be required. If the electroplating is the process that needs to be modified, at least a new process might have to be brought into the firm – usually by the diffusion of

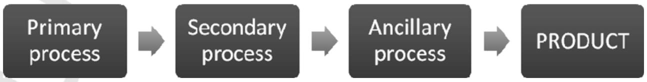

Figure 17.1 The four stages of a production system.

alternative plating technology – but the firm would be expected to be uncomfortable about changing a proven method and taking a chance on altering the appearance of its product, even if it is a separate operation. The most resistance by the firm could be expected by demands affecting the primary process. Here innovation might be necessary and the firm is not likely to invest in developing an entirely new casting process. Even if an alternative casting technology were available, the firm is unlikely to be enthusiastic about changing its core technology.

On the other hand, firms that have already been searching to change even their core technologies because of high energy, water, and materials costs, or for safety and environmental reasons, may be willing to plan for change. However, some firms in transition to new or expanded operation may delay implementing approaches to safety that require new investments if the remaining life of the existing facility, or portions of the facility, is limited. New operations would be expected to be the most receptive to examining technology options that affect core, secondary, and ancillary processes – and even final products.

17.4

Incentives, Barriers, and Opportunities for the Adoption of Inherently Safer Technology

Although they are conceptually similar, pollution prevention and accident prevention differ in the response they have thus far received from industry. Although many firms are embracing pollution prevention (some enthusiastically, some more tentatively), far fewer are moving to primary accident prevention. In all likelihood, this disparity is due to a difference in incentives.

The reasons why firms are embracing pollution prevention and cleaner production today are (1) the increased costs of continuing the current practices of waste transport/treatment and pollution control, (2) liability for environmental damage due to industrial releases of toxic substances, (3) increasingly available information about pollution and toxic releases to the public[4)] , and (4) the EU IPPC Directive [18] and, to a lesser extent, the Pollution Prevention Act of 1990 in the USA [19], which force increased attention to changing production technology, rather than relying solely on end-of-pipe, add-on technologies. Additional requirements in the EU under EMAS [20] and ISO 14000 [21] may also influence the adoption of cleaner technology. Thus, both economic and informational mechanisms are causing a gradual cultural shift away from pollution control and waste treatment towards pollution prevention and cleaner production.

With regard to primary accident prevention, the same economic signals are not really there [2]. Firms do not pay the full social costs of injuries to workers (or to the public) and firms are under-insured. Unlike pollution, which has to be reckoned with as a part of production planning, accidents are rare events and their consequences are

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[4)] The Emergency Planning and Community Right-to-Know Act (EPCRA) has provided firms and the public with plant-specific information revealing large inventories and emissions of toxic substances.

not factored into the planning process. Hence firms may anticipate accidents, and may be motivated to take some steps to avoid them, but they do not feel a strong financial incentive to invest in primary accident prevention. Further, although some of the information reportable under EPCRA is relevant to chemical accidents, this information which is related to actual and mostly expected emissions – without detailed and plant-specific data on production processes – does not allow the firm, or the public, to assess the accident potential of a particular facility.

Furthermore, an organization's expected emissions or wastes can be observed and calculated for any given time period, and this information can be used to measure the effectiveness of the organization's pollution prevention efforts. Because acute chemical accidents are relatively rare events, an organization implementing an effective chemical safety program may therefore receive no form of positive feedback whatsoever. Because the safety system appears to be working, accidents do not occur. Of course, a hazardous chemical plant may eventually receive negative feedback, but only when it is too late to take preventive measures.

In earlier work, Ashford and Zwetsloot [2] summarized the barriers to primary prevention. These include:

1) *Inadequate information* about the potential for catastrophic accidents, the significant costs of secondary prevention and mitigation and the costs of chemical accidents, and the existence of inherently safe[r] alternatives.
2) *Insufficient economic incentives* – in the form of workers' compensation, the tort system, regulatory fines, and insurance.
3) *Organizational and managerial barriers* – linked to corporate attitudes, objectives, structure, and internal incentives, and the lack of a labor–management dialog on safety.
4) *A lack of managerial awareness and expertise* about inherently safe[r] technologies.
5) *Inadequate worker knowledge* about primary accident prevention.
6) *Technological barriers* limiting primary accident prevention.
7) *Regulatory problems*. Primary prevention shares some of these barriers with secondary prevention and mitigation, but these barriers are of different importance.

Although firms sometimes do anticipate accidents and try to avoid them, the expenditures for adequate prevention have not been, and are not likely to be, invested without the right incentives. To the extent that the firm *knows* that the costs of maintenance and the inflexibility of traditional safety approaches are greater than using more reliable, inherently safer approaches, the firm may respond by changing its technology.

One way of providing firms with *more visible* economic incentives would be to encourage them to exploit the opportunity to prevent accidents and accidental releases, (1) by identifying *where* in the production process changes to inherently safer inputs, processes, and final products could be made and (2) by identifying the *specific inherently safer technologies that could be substituted* . The former is termed an Inherent Safety Opportunity Audit and the latter a Technology Options Analysis (TOA) [2, 3]. Unlike a hazard, risk, or technology assessment, these techniques seek to identify *where and what superior technologies could be adopted* to eliminate the possibility, or to reduce dramatically the probability, of accidents and accidental releases[5].

From a general safety perspective, it is widely recognized that safety performance is determined by three elements:

- management and organizational factors
- technological factors
- behavioral factors (also referred to as the human dimension, i.e., people).

These three factors interact and influence the safety of industrial manufacturing and production processes through their effects on the *willingness, opportunity, and capability* of organizations and people to change.

In some approaches that promote the adoption of inherent safety, the emphasis is on mainly technological factors, that is, on identifying and disseminating information on superior technologies. In the current approaches to safety management – especially those falling under the rubric of Safety Management Systems – the emphasis is on management and organizational factors, and also on the human dimension, addressing the management of safety; these approaches assume minimal technological change, implicitly leaving the core and secondary production technologies essentially unchanged. Both of these distinct approaches are by themselves insufficient to maximize the adoption of desirable inherently safer technologies and frustrate further progress in safety performance and continual progress in safety management. There is therefore a clear need, both from a technical point of view and from an industrial practice perspective, for a generally accepted approach that bridges traditional safety management with inherent safer technology.

17.5
Elements of an Inherently Safer Production Approach [2, 3]

17.5.1
Timing and Anticipation of Decisions to Adopt (or Develop) Inherent Safety

It is generally acknowledged that taking action “as early as possible” in the design, planning, and construction of industrial plant is vital for the realization of the most

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[5] A risk assessment, in practice, is generally limited to an evaluation of the risks associated with the firm’s established production technology and does not include the identification or consideration of alternative production technologies that may be inherently safer than the ones currently being employed. Consequently, (risk) assessments tend to invite secondary accident prevention and mitigation strategies, which impose engineering and administrative controls on an existing production technology, rather than primary accident prevention strategies, which utilize input substitution and process redesign to modify a production technology. In contrast to a risk assessment that suggests “fixing the current production system defects, by end-of-pipe additions,” a technology options analysis would expand the evaluation to include alternative production technologies and would facilitate the development of primary accident prevention strategies.

promising options for Inherently Safer Technologies (ISTs). This means that IST principles should be taken into account early in the design process of chemical producing and using plants, or even in the R&D process aiming at developing new technologies for production. This raises questions about how and when organizational and human factors should come into play with technological factors. Technological design and engineering usually precede organizational design and selection of personnel. Hence the early-as-possible principle has a different meaning with respect to managerial and organizational factors. It implies that *organizational procedures must aim at the recognition and early adoption of relevant IST options* in the R&D and in the design stages, before the plant is operational. These may be complemented by other (later) procedures that facilitate the implementation of promising IST options once the scope of production and general plant design are finalized. Both are important organizational elements for the concept of Inherently Safer Production (ISP).

The creation of appropriate internal incentives is also important. With respect to the human dimension, we argue that the *awareness of the key actors* (managers, engineers, researchers, safety experts, operators, and maintenance workers) *should, from the very beginning, be focused on opportunities for IST.* In this way, w*illingness* (on the part of key actors in the firm), as an attitude, can precede the actual knowing of specific options for IST. Achieving this organizational awareness and willingness may require *leadership* of “enlightened” (top) managers. In the management of technology literature, there is the concept of the “technology gatekeeper,” whose technical expertise is crucial for determining what technologies a firm adopts. We similarly use in this chapter the term “managerial gatekeeper” to denote the importance and need for organizational leadership.

It should be emphasized, however, that awareness in industry is not only an issue for individuals. Awareness of individuals is heavily influenced by social factors such as communication and cooperation with other key-actors and by (formal or informal) corporate incentives. Ultimately, awareness in industry is mainly a collective awareness. The collective awareness in a company is greatly dependent on (but also reflected by) the existing *corporate culture*. The corporate culture is known to reflect the real core values of a company (which is not by definition the same as the official core values such as presented in “senior management statements”) on what is being rewarded or not in everyday practice, on subjects and issues that can be addressed or instead are off limits, and on missing elements in the awareness of managers and employees.

Therefore, awareness that influences willingness, and leadership, but also new forms of communication and cooperation and a possible shift in corporate (safety) culture, are all crucial elements for ISP. Good and successful examples set by companies seen as peers may also strongly stimulate industry. Indeed, the production of the same pesticide produced by Union Carbide in Bhopal using a batch process was accomplished by DuPont using an inherently safer continuous flow process.

17.5.2
Life-Cycle Aspects

Another aspect of the time dimension of inherent safety concerns where in the life-cycle of the plant the decision to consider inherent safety arises [22]. It is generally acknowledged that the benefits of inherently safer technologies may persist throughout the life-cycle of a chemical process or plant. This is actually one of the reasons why anticipation of the need for inherent safety is so important; being early can generate more benefits.

However, this all too often leads to the conclusion that IST is not relevant for existing plants, explaining why managers of existing facilities are often not much interested in IST. Their plants seem already technologically determined, and IST seems interesting only as a research or engineering curiosity.

Today's plants are, however, not as technologically rigid as they may seem. Customers ask for tailor-made products, often in small quantities, and delivered as soon as possible. This increases the need for flexibility in plants and processes. Added-on safety usually decreases flexibility because it involves additional safety artifacts such as neutralizing baths, shut-off valves, and bypass piping, whereas inherently safer technologies can increase flexibility because the processes used are often simpler and in any event do not require added-on technology that constrain future modifications.

Furthermore, changes in existing plants take place, and change management is a well-known element of safety management. The methodologies for ISP should therefore be potentially attractive in every stage of the plant/process's life-cycle, and could support the development of a new form of change management that is directed towards inherently safer alternatives.

17.6
A Methodology for Inherently Safer Production

As is the case with the concept of cleaner production, it essential that organizational, human, and economic aspects are, together with technological aspects, integrated into the concept of inherently safer production. Ashford and Zwetsloot [2, 3] developed a methodology for involving the several organizational components of the industrial firm in inherently safer production. The methodology envisions five phases:

- preparatory work, obtaining firm commitment, and designing the focus of the project
- identifying inherently safer options for implementation
- implementation of inherently safer options
- monitoring and evaluating implementation
- evaluation of the final project.

Each phase consists of several sub-phases, and the use of specific tools as listed below. The success of the methodology in the field was explored in a study of Dutch and Greek firms for the European Commission [2, 3] and was analyzed in terms of the *willingness, opportunity, and capability* of the participating firms to adopt and implement inherently safer technologies[6]. *Willingness* is seen as comprising initial commitment, awareness and the will to make a move towards inherently safer technology, and therefore concerns mainly organizational and human aspects. *Opportunity* is seen as a combination of technological and economic aspects: technological options for inherently safer technologies, and the economic attractiveness/feasibility thereof. *Capability* is seen as the organization's capability to *identify and evaluate* inherently safer options, and to *implement* inherently safer options. The methodology appears to be robust and of general use in industry.

The Inherently Safer Production Approach [2] is set out in the list below.

Phase One: Preparatory Work, Firm Commitment, and Focus of the Project:

1) **Start-up and Obtaining Commitment from the Firm**
   This first step entails obtaining general commitment and cooperation from management, selecting possible (parts of the) plant/unit/process/division, obtaining the specific commitment of the management of that (part of the) plant/unit/process/division, and formulating and formalizing the project goals and project plan.

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6) The importance of these three factors was first developed in the context of necessary and sufficient conditions for stimulating pollution prevention or cleaner production technologies [23]. The three affect each other, of course, but each is determined by more fundamental factors [24].

Willingness is determined by (1) *attitudes towards changes in production in general*, by (2) *knowledge about what changes are possible*, and by (3) *the ability to evaluate the options*. Improving the last two involves aspects of capacity building, whereas changing the first may be more idiosyncratic to a particular manager or alternatively a function of organizational structures and reward systems. The syndrome "not in my term of office" describes the lack of enthusiasm of a particular manager to make changes whose benefit may accrue long after they have retired or moved on, and which may require expenditures in the short or near term.

Opportunity involves both supply-side and demand-side factors. On the supply side, technological gaps can exist (1) between the technology used in a particular firm and the already-available technology that could be *adopted or adapted* (known as diffusion or incremental innovation, respectively), and (2) the technology used in a particular firm and technology that could be *developed* (i.e., major or radical innovation). On the demand side, four factors could push firms towards technological change – whether diffusion, incremental innovation, or major innovation: (1) regulatory requirements, (2) possible cost savings or additions to profits, (3) public demand for safer industry, and (4) worker demands and pressures arising from industrial relations concerns.

Capacity or *capability* can be enhanced by both (1) increases in knowledge or information about inherent safety opportunities, partly through formal Technology Options Analyses or Inherent Safety Opportunity Audits, and partly through serendipitous transfer of knowledge from suppliers, customers, trade associations, unions, workers, and other firms, in addition to reading about safety issues, and (2) improving the skill base of the firm through educating and training its operators, workers, and managers, on both a formal and informal basis. Capacity to change may also be influenced by the inherent innovativeness (or lack thereof) of the firm as determined by the maturity and technological rigidity of particular product or production lines [24]. The heavy, basic industries, which are also sometimes the most unsafe industries, change with great difficulty, especially when it comes to core processes.

Finally, it deserves re-emphasizing that it is not only technologies that are rigid and resistant to change. Personal and organizational flexibility is also important.

2) **Initial Design and Preparation**
   This step involves the establishment of an internal *project team* within the selected plant/division, assisted by the external consultants, to construct the project plan.
3) **Conduct a Traditional Safety Audit**
   This safety audit is used for identifying inputs and material flows, processes and intermediates, and final products – *but* with special attention paid to human–material/process/equipment *interactions that could result in (a) sudden and accidental releases/spills, (b) mechanical failure-based injuries, and (c) physical injuries – cuts, abrasions, and so on, as well as ergonomic hazards*. Additional sources of adverse effects/safety problem areas are records/knowledge of in-plant accidents/near misses, equipment failures, customer complaints, inadequate secondary prevention/safety procedures and equipment (including components that can be rendered non-operable upon unanticipated events), and inadequacies in suppliers of material and equipment or maintenance services.
4) **Selection of Candidate Processes or Operations Within the Firm**
   This step entails the selection of candidate processes or operations within the firm that warrant special attention. The discovery of *where* the process could benefit from the adoption of IST is the outcome of an Inherent Safety Opportunity Audit done within this and the next tasks. The criteria for identifying these include three categories: (a) general safety information, (b) symptoms of inherent unsafety, and (c) inefficiency of safety management.

***Phase Two: Identifying Inherently Safer Options for Implementation**:*

5) **Functional Review**
   This step reviews the *functional purposes* of materials, equipment, processes, and operations – noting obvious inefficiencies in material/water/energy use and gradual pollution, and obvious hazards due to spatial combinations of functions.
6) **Specific Set of Search Questions**
   This step constructs *a specific set of search questions* to guide identification of opportunities for material substitution, equipment modification/substitution, changes in work practices and organization, modifications in plant layout, and changes in final product.
7) **Brainstorming to Generate Inherently Safer Options**
   This step involves the planning of creative brainstorming sessions by the project team to generate as many initial options as possible.
8) **Construction of a Search Process for Information on Inherently Safer Options/Alternatives**
   This step involves planning the process of using external potentially useful information sources, including so-called "solution databases" (such as compiled by Lyngby, the Danish EPA and TNO), safety performance/benchmarking data, literature on process safety and reliability, literature on cleaner production/pollution prevention, academic experts/researchers –

including the TNO Work and Employment/Ergonomic project staff, in-plant expertise including plant workers/union, suppliers, equipment manufactures, other domestic firms, foreign firms and technology, and national/international unions.

9) **Identification of Promising Inherently Safer Options**
Identification of promising alternatives/options for materials, equipment, processes, operations, work practices and organization.

10) **Design of a Consistent Set of System Changes**
With the involvement of both production and safety/environmental personnel, design internally-consistent sets of 2–3 alternative overall system changes encompassing multiple component changes related to point **9** above.

11) **Feasibility Study**
Conduct feasibility studies utilizing rough relative economic (cost) and safety assessment for these 2–3 system changes. Also included are environmental impacts and organizational impacts and requirements.

12) **Commitment of the Project Team**
Present results of the feasibility studies to the project team and obtain their commitment an endorsement.

13) **Recommendations to Management**
Recommend system changes to the firm management.

Phase Three: Implementation of Inherently Safer Options:

14) **Facilitate Decision-Making**
Mobilize the decision-making processes within the plant/unit to implement the selected system, recognizing overall firm imperatives and constraints.

15) **Preparation of Implementation**
Work with in-plant personnel (both production and safety/environmental people, and the safety and health committee) to design a general approach to changes in the plant/unit.

Phase Four: Monitoring and Evaluating Implementation:

16) **Monitor Actual Design Changes**
This step involves the in-plant project team in the monitoring and evaluation of the progress and success of the implemented options/system on the bases of safety, quality, technology, costs, and environmental impact.

Phase Five: Final Project Evaluation:

17) **Evaluation of Overall Project**
This final step involves the project team in evaluating the outcome of the inherent safety project in the firm and formulating additional recommendations. This includes the results of plant management evaluation.

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Abstract

It is now generally recognized that in order to make significant advances in accident prevention, the focus of industrial firms must shift from assessing the risks of existing production and manufacturing systems to discovering technological alternatives, that is, from the identification of problems to the identification and design of solutions. Encouraging the industrial firm to perform (1) an inherent safety opportunity audit (ISOA) to identify where inherently safer technology is needed, and (2) a technology options analysis (TOA) to identify specific inherently safer options, will advance the adoption and design of primary prevention strategies that will alter production systems so that there are fewer inherent safety risks . Successful approaches require both technological and managerial changes. Firms must have the willingness, opportunity, and capability to change.

Keywords: physical hazards; safety; chemical production; safer production; safer chemicals; green chemistry.

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