

# Industrial safety: the neglected issue in industrial ecology

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## Introduction

In the enthusiasm to address the problems from 'gradual' pollution of the environment stemming from *expected* byproducts and waste of industrial, agricultural, transportation and extraction activities, an important consideration that has received relatively little attention among firms and government is the *sudden and accidental releases of chemicals (with attendant energy consequences)* that affect both workers and communities. While O'Rourke *et al.* (*Int. J. Environment and Pollution*, 1996, 6(2/3), 89-112) do focus on the important omissions of the consideration of energy flows, (dissipative) products after they leave the industrial ecosystem, and consumption patterns, they make only passing reference to the importance of addressing worker health and safety in their discussion of the limitations of Industrial Ecology.

While Industrial Ecology is being touted as a new all-encompassing paradigm, the centerpiece, as practiced, is the creation of an industrial ecosystem involving firms which often concentrate and then exchange materials and waste so as to minimize the costs and environmental effects of the disposal and incineration of waste, and toxic emissions to air, water, and soil. The organizing principle for implementing Industrial Ecology concepts among the exchange partners can be a concern for materials containing a *common substance* (e.g. a metal; see Sagar and Frosch, this volume), an *industrial sector* (e.g. petrochemicals), or a *geographical area* (e.g. Kalundborg).

A pollution prevention/cleaner production focus differs from that of the Industrial Ecology centerpiece in that it argues preferentially for reduction of pollution 'at the source' through input (feedstock) substitution, process re-design, and re-formulation of final product (see Oldenburg and Geiser, this volume). Some commentators have pleaded for an integrated approach incorporating both concepts, as well as a healthy dose of end-of-pipe *pollution control* where appropriate.

This article argues that both pollution prevention/cleaner production *and* waste and material exchange, as currently practiced, pose the risk of 'media shifting' from environmental problems to worker (and sometimes community) health and safety problems, for different reasons and with different consequences. Examples are drawn from a study of this media shifting found in cleaner production databases<sup>1</sup>, and from generic examples of materials and waste exchange. First, however, the concept of promoting *inherently safer technologies* through primary accident prevention is introduced.

## Inherent safety

Inherent safety is an approach to chemical accident prevention that differs fundamentally from secondary accident prevention and accident mitigation<sup>2-5</sup>. 'Inherent safety'—sometimes also referred to as 'primary prevention'—relies on the development and deployment of technologies that prevent the *possibility* of a chemical accident.\* By comparison, 'secondary prevention' reduces the *probability* of a chemical accident, and 'mitigation' and emergency responses seek to reduce the *seriousness* of injuries, property damage, and environmental damage resulting from chemical accidents.

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\*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 *safer*. 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 byproducts in a violent way. Thus, 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.

Secondary prevention and mitigation, by themselves, are unable to eliminate the risk of 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<sup>6</sup>. 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. Normal accidents arising in these systems result in significantly less harmful chemical reactions or releases. Replacement of existing production systems by such benign chemical processes—sometimes called 'green chemistry'—as well as non-chemical approaches, are examples of primary accident prevention.

Inherent safety is similar in concept to pollution prevention. Both attempt to prevent the possibility of harm—from accidents or pollution—by eliminating the problem at its source. Both typically involve fundamental changes in production technology discussed above: substitution of chemical inputs, process redesign, or final product reformulation.\* Secondary prevention and mitigation, meanwhile, are similar in concept to pollution control and remediation measures, respectively, in that each involves only minimal change to the core production system.

The superiority of pollution prevention as a tool of environmental policy has been recognized for more than a decade<sup>7</sup>. The 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<sup>8</sup>. In 1990, Congress codified, as national environmental policy, a preference for pollution prevention over pollution control, when it passed the Pollution Prevention Act.† The logic underlying the superiority of a preventive approach applies equally well to chemical safety as to environmental protection. However, inherent safety measures need to be integrated with pollution prevention, so that media shifting does not occur.

The reason why firms are embracing pollution prevention today is that:

1. It has become very expensive to continue the current practices of waste transport/treatment and pollution control; the firms clearly find it in their own interest to adopt pollution prevention.
2. The Superfund Act (SARA Title III) created joint and several liability for environmental damage due to industrial releases of toxic substances.

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\*Although inherent safety and pollution prevention are similar in concept, there are practical differences between the two that have, so far, made adoption of inherent safety measures less attractive to industry than pollution prevention. These are discussed later in the article.

†42 U.S.C. §13101, *et seq.*

3. The Emergency Preparedness and Community Right to Know Act (EPCRA) has provided firms and the public with the *information* that revealed large inventories and emissions of toxic substances.

Thus both economic and informational mechanisms are causing a gradual cultural shift away from pollution control and waste treatment and towards pollution prevention.

With regard to primary accident prevention, the economic signals are not really there. 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 not factored into the planning process.

Furthermore, an organization's gradual 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 is working, accidents do not occur. Of course, a hazardous chemical plant may receive negative feedback, but only when it is too late to take preventive measures.

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. One way of providing the right economic incentives would be to require firms to identify inherently safer technologies through the undertaking of Technology Options Analysis which, unlike a hazard or technology assessment, seeks to identify superior technologies that *could be adopted* to eliminate the possibility, or to dramatically reduce the probability, of an accidental release.\*

### Pollution prevention and cleaner technology

There is a great deal of effort being devoted in both North America and in Europe to the identification of pollution prevention/cleaner technology opportunities. In the USA, the EPA has created the Pollution Prevention Information Clearinghouse, which contains elec-

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\*A hazard 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, hazard assessments tend to emphasize 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 hazard assessment, a technology options analysis would expand the evaluation to include alternative production technologies and would facilitate the development of primary accident prevention strategies.

tronic information on promising technologies. The United Nations Environmental Programme (UNEP) has created a similar system, the International Cleaner Production Information Clearinghouse (ICPIC) drawing upon US, European and other sources.

In a project conducted for the European Commission, Directorate for Health, Safety, and Public Health (DG-V), the author and his colleagues<sup>1</sup> examined a representative selection of cases in the ICPIC system. Summary observations and criticisms of the content of the ICPIC cases are:

- *The most striking feature of the case studies is their complete lack of information regarding the interactions of human beings with the production processes, materials, or products.* Process engineers generally do not consider workers or jobs as part of the production process. Manufacturing engineers often can not answer the question 'Where do workers fit into your new framework of process design for the environment and for product safety?' From a worker health perspective, this is a serious problem that must be solved if risk shifting from the environment to people is to be limited.
- *No information is given regarding the physical or economic context for the processes.* It is very difficult to know what the processes in the UNEP [ICPIC] database actually looked like with respect to the physical space in which they were located, the degree of automation, the quality and maintenance status of the equipment, engineering controls, or administrative practices used to run the processes including shift work. From an industrial hygiene perspective, it is well known that the actual conduct of the processes described in these case studies can vary considerably depending on the economic context and physical surroundings of the workplace. Many of these processes are used in the USA, Italy, and China and, in each of these countries, chemical manufacturing is performed using practices that range from manual reactor vessel charging, mixing, packaging, and maintenance to process steps that are almost completely enclosed and automatic. The same process under these different conditions could have very different implications for worker health.
- *Limited information is given regarding the physical form of the substances at certain stages in the process so that, should a worker be exposed, the physiologic route of entry can not be adequately anticipated.* The physical form of substances can occasionally be determined by knowing process specifications such as temperature and pressure but these process specifications are not given consistently. Information is lacking about the manner in which materials are added to a process, maintained, stored and disposed.

The authors undertook an in-depth analysis of eight technologies in the ICPIC system that represented a process or product line that has significance for the EU from an economic or industrial policy perspective.

The features for the eight technologies are represented in *Table 1*. The first four technologies actually worsen the health and safety of workers. Cases 5, 6 and 8 describe technologies that do not trade off environmental benefits for worsened worker health and safety but, on the other hand, are suboptimal from a worker protection perspective. That is, in cases 5, 6 and 8, missed opportunities for even better environmental and worker protection performance were identified. Case 7 represents an example of a technology with both characteristics: the substitution of fluorocarbons by hydrocarbons introduces a risk of explosion (creating an adverse effect for workers); the use of multi-process wet cleaning would eliminate both the use of fluorocarbons and hydrocarbons (a missed opportunity). Other examples from the literature include the substitution of HCFCs for CFCs, leading to lessened damage to the ozone layer, but creating a carcinogenic risk for workers, and the use of water-based paints, eliminating volatile organic solvents, but introducing a biocide hazard for workers.

These examples demonstrate that a focus on either gradual pollution or on environmental concerns can overlook problems created or missed with regard to worker health or sudden and accidental releases. Waste and materials exchange create similar, but different problems.

### **Industrial metabolism and the increased risk of sudden and accidental releases**

As aptly analyzed by O'Rourke *et al.* (this volume), casting a net narrowly around a problem and optimizing the identified factors can lead to 'disconnects' in environmental, energy, and worker safety policies, and with the broader concept of sustainability. The practices of concentrating waste and byproducts, handling them, and transporting them can increase the probability and opportunity for worker exposure to toxic substances—and both the probability and magnitude of the risk of explosions, fires, and acute toxic episodes from sudden and accidental releases.\* Examples include the concentration of carcinogenic chromium(VI) compounds, volatile organic waste products, and unstable chemical mixtures in waste.

Moreover, industrial metabolism is driven by a concern for minimizing (really optimizing) *expected* gradual pollution (but not rare unexpected catastrophic events) based on cost, health and ecosystem considerations relevant to, and predictable by, *the firm*. Indeed, a distinction should be drawn between 'full cost accounting' (misleadingly named because it encompasses only those factors important to, or costs borne by, the firm) and 'social cost accounting', which

\*Risk factors associated with hazardous substance releases at fixed facilities or during transport that have *public health* consequences include ammonia, pesticides, volatile organic compounds, acids, and petroleum products<sup>9</sup>. Sudden releases or spills leading to worker exposures involve many more substances than affect the community.

**Table 1** Characteristics of selected cleaner production technologies

Case no.	Technology	Type	External pollution or waste status	Worker health status	Accident potential status	Raw material use	Water use	Energy efficiency
1	Rapeseed oil extraction by enzymes	Adverse for workers	++	—	+	++	-	—
2	Flame spray zinc	Adverse for workers	+	-	(0,-)	n/a	++	(0, +)
3	Recovery of sulphated mother liquor	Adverse for workers	+	-	—	++	++	(0, +)
4	Recycling of cyanide water	Adverse for workers	++	—	—	++	0	(0, +)
5	Solvent substitution in paint	Missed opportunity	+	0	0	+	0	n/a
6	Production of casting molds	Missed opportunity	++	+	+	+	0	0
7	Hydrocarbon-based dry cleaning	Missed opportunity and adverse for workers	++	0	(0,-)	n/a	-	-
8	Wood and furniture surface treatment	Missed opportunity	+	0	0	+	0	0

++ , significant improvement; + , improvement; 0, no change; -, deterioration; —, significant deterioration; n/a, information not available.

addresses all flows to the society. Firms are driven by full cost accounting and this accounting is unlikely to include the unexpected and unpredictable costs of chemical accidents. Thus, technologies and measures that eliminate the probability or reduce the possibility of accidents are unlikely to be searched or adopted, and changes in industrial practices that actually increase the probability of accidents will be allowed to be implemented.

**Policy implications of recent government initiatives**

In both the USA and the European Community, attempts have been made to deal directly with sudden and accidental releases. However, seriously lacking is an integration of these concerns with legislation, regulations and policies addressing gradual pollution, pollution prevention, and industrial ecology.

Section 304 of the Clean Air Act (CAA) of 1990 directed the US Occupational Safety and Health Administration (OSHA) to promulgate a chemical process safety standard to prevent accidental releases of chemicals which could pose a threat to employees,\* and Section 112(r) of the CAA directed the EPA to develop regulations, including a risk management plan (RMP), to prevent chemical accidents.† While OSHA complied with the requirements of the CAA by promulgating a process safety management (PSM) standard on 24 February 1992,‡ EPA did not promulgate its RMP rule, as required by the CAA, until 20 June

1996.\* The PSM standard is designed to protect employees working in facilities that use 'highly hazardous chemicals', and employees working in facilities with more than 10 000 pounds of flammable liquids or gases present in one location. The list of highly hazardous chemicals in the standard includes acutely toxic, highly flammable, and reactive substances. The PSM standard requires employers to compile safety information (including process flow information) on chemicals and processes used in the workplace, complete a workplace process hazard analysis every 5 years, conduct triennial compliance safety audits, develop and implement written operating procedures to maintain the integrity of process equipment, conduct extensive worker training, perform pre-startup reviews for new (and significantly modified) facilities, develop and implement written procedures to manage changes in production methods, establish an emergency action plan, and investigate accidents and near-misses at their facility.

OSHA's PSM standard contains various mechanisms to induce firms to identify and to minimize the chemical hazards posed by their production technology. In essence, however, the PSM standard seeks only to improve safety *management* in facilities likely to experience sudden and accidental releases of highly hazardous chemicals that may injure workers. It imposes no affirmative duty to identify inherently safer production alternatives or to change any element of the facility's actual production system. For that reason, the main effect of the PSM standard is to stimulate secondary prevention and mitigation measures.

\*42 U.S.C. §7604.  
 †42 U.S.C. § 7412(r).  
 ‡29 C.F.R. §1910.119.

\*40 C.F.R. Part 68.

EPA recently promulgated regulations setting forth requirements for the 'risk management plans' specified in the Clean Air Act.\* The RMP rule is estimated to apply to some 66 000 facilities with processes that contain more than a threshold quantity of a regulated substance. All applicable processes are placed into one of three possible categories ('Programs') depending on the results of a hazard assessment (involving an offsite consequence analysis—including worst-case risk scenario—and compilation of a 5-year accident history).

Program 1 requirements apply to processes which have not had an accidental release with offsite consequences during the previous 5 years and for which a worst-case release would not affect the public. Program 3 requirements apply to higher risk, complex chemical processing operations and processes already subject to OSHA's PSM standard (but not eligible for Program 1). All other covered processes must satisfy Program 2 requirements.

The owner or operator of any covered process must:

- (1) prepare and submit a single risk management plan (RMP)—revised at least once every 5 years—covering all affected process and chemicals, to demonstrate compliance with all the requirements of the standard;
- (2) prepare and document the hazard analysis. For Program 1 processes, the additional requirements are minimal:
  - (1) ensure that emergency response procedures are coordinated with community response organizations to verify eligibility for Program 1;
  - (2) completion of a Program 1 certification.

Program 2 processes must document a management system, implement a more extensive, but still streamlined prevention program, and implement an emergency response program. Program 3 requirements, which are the most stringent, include documentation of a management system, implementation of a prevention program that is fundamentally identical to the requirements of the OSHA PSM standard, and implementation of an emergency response program.

EPA's RMP rule addresses many but not all recognized barriers to chemical accident prevention. For example, the requirement that all firms owning or operating covered processes conduct an offsite consequence analysis, including developing worst-case accident scenarios, will help these firms to appreciate the magnitude and effects of a possible serious chemical accident. Similarly, the RMP rule requirement that all covered firms prepare and submit a 5-year accident history will bring about significant improvements in accident reporting, even though inclusion of near misses is not required as part of the accident history.† In addition, the requirement that all covered firms prepare

and submit a risk management plan promises to improve their accident prevention planning. However, the RMP requirements are flawed in that the plans need be revised only every 5 years, rather than annually, and particularly because facilities qualifying for Program 3 are not required to perform a technology options analysis (TOA) as part of the RMP.

EPA formally entertained, in a Supplemental Notice of Proposed Rulemaking (SNPRM) on the draft RMP rule,\* the possibility of requiring covered facilities to perform a TOA to identify possible inherently safer technologies but, despite more than two dozen comments in response to the SNPRM recommending a mandatory TOA† and other recommendations from one of EPA's grantees<sup>10</sup>, EPA chose not to impose such a requirement. Instead, EPA concluded that the requirements under OSHA's PSM rule, such as a process hazard analysis (which permits, but does not require, consideration of alternative production technologies) and a pre-startup safety review for new or significantly modified facilities (undertaken *after* plant design and construction), were adequate to prevent chemical accidents—despite acknowledgment by EPA in the SNPRM on the draft RMP rule the advantage of conducting TOAs at the design stage or earlier.‡

Hence, EPA's RMP rule is subject to most of the same deficiencies and limitations as OSHA's PSM rule when it comes to inherent safety. Rather than focusing on the need to promote technological change, EPA's RMP rule takes the technologies of production *as a given*, and thus fails to encourage significant changes in chemical processes, final products, or inputs.§ As a result, the principal effect of the RMP standard will be to encourage secondary accident prevention and mitigation. Furthermore, by not requiring a TOA by the covered facilities—those qualifying for Program 3 under the RMP rule—EPA is abandoning probably the most effective mechanism to coordinate pollution prevention and primary accident prevention. After all, both pollution prevention and inherent safety typically

\*See 60 *Federal Register* 13535 (13 March 1995).

†There were also numerous comments opposing either the concept of a TOA or the imposition of TOA requirements as part of the RMP rule. See 61 *Federal Register* 31699 (June 20, 1996).

‡See 60 *Federal Register* 13535 (13 March 1995).

§Further, it appears that the new rule is actually in violation of the duties imposed upon EPA in the Pollution Prevention Act (PPA) of 1990 which is not limited to gradual releases (i.e. pollution), but includes sudden and accidental releases as well. Indeed, Section 6607(b)(7) requires as an item to be reported by owners or operators of covered facilities '[t]he amount of any toxic chemical released into the environment which resulted from a catastrophic event, remedial action, or other one-time event, and is not associated with production processes during the year'. Section 6604(b) of the PPA states that as part of a strategy to promote source reduction, 'the Administrator shall (1) ensure that the Agency considers the effect of its existing and proposed programs on source reduction efforts and shall review regulations of the Agency prior and subsequent to their proposal to determine their effect on source reduction...[and] (5) facilitate the adoption of source reduction by businesses'. Certainly, EPA, in ignoring primary accident prevention approaches and failing to encourage or facilitate these approaches through the identification of superior technological options, violates the spirit if not the letter of the PPA.

\*See 61 *Federal Register* 31668, *et seq.* (20 June 1996), codified at 40 C.F.R. Part 68.

†Only those accidents from covered processes that resulted in deaths, injuries, or significant property damage on-site, or known off-site deaths, injuries, evacuations, sheltering in place, property damage, or environmental damage must be included the 5-year accident history. Near-miss accidents (that did not meet any of the previous criteria) need not be included.

involve fundamental changes in production technology that, applied on a firm-specific basis, are difficult to legislate. The more reasonable approach, common to both pollution prevention and inherent safety, is to require covered facilities to go through a planning process to investigate pollution prevention/inherent safety technologies options that might ultimately lead to their adoption.

It must be candidly recognized that firms object to having to identify superior technologies for accident prevention in a formal, reportable way, because, if the firms acknowledge their existence, the technologies are relatively easy to adopt, and the firms do not implement the desirable changes, this increases their exposure to lawsuits in the event that a preventable chemical accident occurs. This is not the case for pollution prevention, because the causal link between gradual pollution in the environment and environmental disease is so difficult to establish. This is undoubtedly one of the reasons why objections have been raised by industry. Technology option analyses are not expensive to do, or to report. The record accumulated for the then proposed rule documents that firms reported they were either already identifying superior technologies\* and hence argued there was no need for the formal requirements, or they were not doing them—even though there would be a benefit to doing so. If firms are already doing TOAs, formalizing the requirement would not add a significant burden. If they are not doing them, but they should be, a formal requirement would be beneficial and justified.

Government should play a much more active role in developing and disseminating information about accident prevention, especially primary accident prevention. The federal government, under the direction of EPA and/or OSHA, could create a clearinghouse of information about inherently safer technologies, including cost and performance data. Possibly, EPA's Pollution Prevention Information Clearinghouse could be expanded to include this information. Information submitted by a firm in its technology options analysis might contribute to the federal government's information base; conversely, information provided by the clearinghouse might be utilized by firms in conducting TOAs.

At the state level, government could develop technical assistance initiatives, including demonstration projects of primary prevention measures. Such technical assistance programs can significantly reduce the technological risks which frequently inhibit firms—particularly small- and medium-sized firms with limited technological capabilities—from adopting inherently safer technologies. Because industry often fears or distrusts the actions of government, the state agencies should utilize trained private consultants, acting under

contract to the state, to provide the technical assistance whenever possible.\*

In 1982, the European Union adopted the famous EU Directive (82/501/EEC) 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<sup>14</sup>. A revised version of the Seveso Directive came into effect in February 1997. It strengthens the original provisions and coverage of accident-prevention activities, as well as broadens the types of installations that must comply. Particularly worthy of note is the mention of inherent safety as a preferred approach to preventing chemical accidents in the accompanying Guidance for the Development of the Safety Report.

## Conclusion

Industrial ecology, narrowly conceived as waste and materials exchange, or broadly conceived to include pollution prevention, is unlikely to address the sudden and accidental release of chemicals. Because of the relatively rare occurrence of serious chemical accidents compared to the expected gradual releases of pollution and the generation of waste, primary accident prevention involving fundamental changes such as input (feedstock) substitution, re-design of process, and reformulation of final products is unlikely to be undertaken to improve safety. Thus there are certain-to-be-missed opportunities to improve safety. More seriously, however, is the enhanced likelihood that industrial ecology initiatives actually increase health or safety risks for workers, either (1) because of more concentration of wastes and recovery, exchange and transport of materials and waste, which pose more risks for workers, or (2) because of input substitutions and process changes, made to improve the environment, which actually pose health or safety hazards (such as shifting to HCFCs or non-CFC organic cleaning agents). Only a comprehensive examination of technology options that is broadly conceived will co-optimize the achievement of environmental performance, safety, and material and energy utilization.

## References

- 1 Ashford, N., Banoutsos, I., Christiansen, K., Hummelose, B. and Stratikopoulos, D., Evaluation of the Relevance for Worker Health and Safety of Existing Environmental Tech-

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\*There is a small core of US industry safety professionals who are dedicated to inherent safety principles<sup>11,12</sup>. Unfortunately, they do not represent the mainstream.

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\*If necessary, the state may have to provide the private consultants with training in primary accident prevention. Such state involvement in training should ultimately help create a technical consulting market in primary accident prevention to replace or augment the existing market in secondary prevention and mitigation (see Ashford *et al.*<sup>13</sup>, p. V-20).

- nology Data-bases for Cleaner and Inherently Safer Technologies. A Report to the European Commission, April 1996.
- 2 Ashford, N. A., in *Proceedings of Enprotech '91 International Environmental Conference*, Taiwan, 30–31 January 1991.
  - 3 Kletz, T. A., *Cheaper, Safer Plants or Wealth and Safety at Work*. The Institution of Chemical Engineers, Rugby, UK, 1984.
  - 4 Kletz, T. A. *Process Safety Progress*, 1989, **85**, 18–26
  - 5 Kletz, T. A., *Plant Design for Safety*. Hemisphere Publishing Corporation, New York, 1991.
  - 6 Perrow, C., *Normal Accidents: Living with High-Risk Technologies*. Basic Books, New York, 1984.
  - 7 Caldart, C. C. and Ryan, C. W. *Hazardous Waste and Hazardous Materials*, 1985, **2**(3), 309–331
  - 8 Hirschhorn, J. S. and Oldenburg K. U., *Prosperity Without Pollution: The Prevention Strategy for Industry and Consumers*. Van Nostrand Reinhold, New York, 1990.
  - 9 Hall, H. I., Haugh, G. S., Price-Green, P. A., Dhara, V. R. and Kaye, W. E. *American Journal of Public Health*, 1996, **86**(6), 855–857
  - 10 Ashford, N. A., Gobbel, J. V., Lachman, J., Matthiesen, M., Minzner, A. and Stone, R. F., *The Encouragement of Technological Change for Preventing Chemical Accidents: Moving Firms from Secondary Prevention and Mitigation to Primary Prevention*. Center for Technology, Policy and Industrial Development, Massachusetts Institute of Technology, Cambridge, Massachusetts, July 1993.
  - 11 Lutz, W. K. *Process Safety Progress*, 1995, **14**(3), 153–160
  - 12 Hendershot, D. C., 'Inherently Safer Plants', Chapter 2 in *Guidelines for Engineering Design for Process Safety*, ed. Center for Chemical Process Safety. American Institute of Chemical Engineers, New York, 1993.
  - 13 Ashford, N. A., Cozacos, A., Stone, R. F. and Wessel, K., The Design of Demonstration or Experimental Programs to Encourage Waste Reduction: An Incentives Analysis. Final Report to the New Jersey Department of Environmental Protection, Division of Science and Research, 1988.
  - 14 Von Moltke, K. *The Environmental Forum*, 1985, **June**, 21–23