INTEGRATING PROCESS SAFETY INTO ChE EDUCATION AND RESEARCH

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Accident statistics for 1989 from the Accidental Release Information Program (ARIP) of the U.S. Environmental Protection Agency[1] are shown in Figure 1. These statistics cover catastrophic and unplanned releases of chemicals into the atmosphere. They underline the fact, however, that a large number of accidents and catastrophic releases occur because of design flaws, wrong equipment specifications, and lack of or disregard for operating and maintenance procedures. The boardroom perspective on the cause of these accidents and what to do about them varies, but many believe that safety in the process industry is of primary importance and is critical to the industry's continuing "license to operate."

The total number of process plant accidents cannot be accurately estimated because of underreporting, but the number is large and many people, both workers and the public, are adversely affected by the accidents. For example, in 1991 the National Response Center received over 16,300 calls reporting the release or potential release of hazardous chemicals.[2] Another study[3] analyzed the EPA's Emergency Response Notification System database of chemical accident notifications and found that from 1988 through 1992, an average of nineteen accidents occurred each day, *i.e.*, more than 34,500 accidents involving toxic chemicals occurred over the five-year period. The promulgation of the Toxic Release Inventory Reporting requirements[4] as part of the Clean Air Act Amendments of 1990 led to the submission of toxic release information that clearly delineated the number and extent of toxic chemical releases and their potential impact on the public and on the environment. The university plays a critical role in changing this situation.

Change in population demographics, increasing awareness of process plant hazards, and above all, the continuing threat of a chemical catastrophe continue to provide the impetus for governments to develop legislation for eliminating or minimizing the potential of such accidents. International efforts include the Seveso Directive covering members of the European Community. Other nations have similar laws, such as the Sedesol guidelines in Mexico for performing process risk audits, and the post-Bhopal accident-prevention law in India. The World Bank has developed guidelines for identifying and controlling hazards, and the International Labor Organization has developed a code of practice for preventing major accidents.

In 1990, the U.S. Congress enacted the Clean Air Act Amendments (CAAA), which directed the Occupational

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Safety and Health Administration (OSHA) and the Environmental Protection Agency (EPA) to develop standards for reducing the frequency and severity of chemical plant accidents. In keeping with the congressional mandate, OSHA promulgated the Process Safety Management (PSM) rule, intended to protect workplace employees. Similarly, EPA promulgated its risk-management program rule in 1996 to protect the public and the environment. In the United States, federal agencies are not the only government regulators active in the chemical accident prevention arena. Several states have empowered their health, safety, and environmental agencies to create regulations requiring companies to establish and practice specific programs to improve safety.

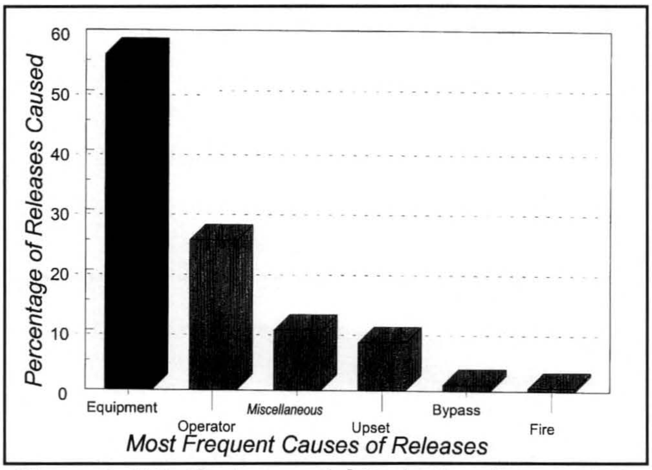

Figure 1. *U.S. Environmental Protection Agency statistics on Accidental Release Information Program, 1989.*

Laws and regulations are logical reactions to catastrophic process plant accidents. But can the mere promulgation and enforcement of laws and regulations actually affect the frequency and severity of process plant accidents? The philosophical issue is that we can only regulate something for which we have knowledge and understanding. For example, OSHA process safety management regulations require facilities to develop and implement management of change procedures. That is, before a process change is implemented, engineers must evaluate the change and ensure that it is technically sound and cannot result in a hazardous situation. The evaluation could consist of a hazard and operability (HAZOP) study conducted by a multidisciplinary team using some HAZOP software available in the marketplace.

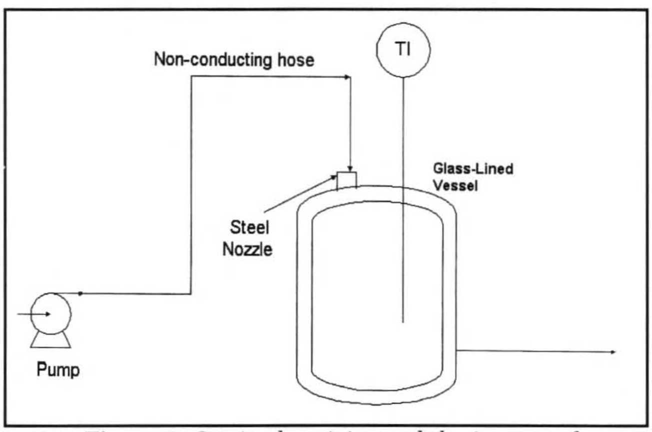

Figure 2. *Static electricity and the impact of process changes.*

For the process shown in Figure 2, consider the addition of an organic A with a certain thermal conductivity to the glass-lined reactor. During the original design, engineers made necessary calculations to ensure that the voltage and ignition energy caused by static electricity did not exceed the dangerous limits of 350 V and 0.1 mJ, respectively. Above these limits there exists a potential for spark and possible fire and explosion. But in response to market demands for product specifications, the plant is planning a switch to organic B, the only difference in thermophysical properties being a slight increase in thermal conductivity. The calculations now show that the voltage and ignition energy caused by the static electricity exceeds the dangerous limits. The most important question is whether we make this determination as part of an after-the-fact accident investigation or as part of the management of change process. If we choose the latter, we must understand the gravity of the problem and take appropriate corrective and remedial measures. These measures may include installation of additional grounding, control of flow rate to reduce static electricity, and relaxation (hold time to allow for charge reduction).

In addition to the above issues, the issues of inherent safety in process design, equipment selection, and operating and maintenance procedures depend to a large extent on a fundamental understanding of the underlying science and application of those principles to the problem at hand. For example, in design and construction of a polyethylene plant that uses a large amount of flammables at very high pressures and temperatures, the inherent hazard is that any accident has the potential of releasing large quantities of the flammable, which because of the thermodynamics can likely flash and form an aerosol. While "bells and whistles" can be added after the fact to make the process extrinsically safer, the comprehensive education and research approach suggested in this paper equips the engineer to come up with an intrinsically safer process during the design and construction phase. Some solutions may include intensification, substitution, attenuation, or limitation of effects. These concepts, while available in some literature,[5-7] are not covered adequately in chemical engineering instruction and research.

What can we do to fix or reduce the extent of the fundamental problem described here? The challenge is how to create a culture in which consideration of process safety issues is second nature, driven by a total understanding of the underlying engineering, process chemistry, and other factors. While regulations, plant policies and procedures, and industry standards accomplish much, universities must play a significant role in addressing this challenge. The role of engineers has changed dramatically, and as a result, universities must provide an integrated engineering education that equips engineers not only with the classical fundamental subjects (thermodynamics, fluid mechanics, reaction kinetics), but also provides them with an understanding of process safety engineering and how they can use their knowledge of fundamental engineering subjects to make the process plant safer. The need is not the establishment of a new discipline, but one of fine tuning the engineering curriculum. To this end, Texas A&M University established the Mary Kay O'Connor Process Safety Center, an industrially sponsored Center of Excellence, to produce engineers trained in process safety and to provide industry with the research base it needs to compete successfully in the global marketplace.

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The Center charter is to broaden the scientific and engineering knowledge base of industry and to educate engineers and scientists in the field while striving to achieve technological breakthroughs necessary to reach ambitious long-term, systems-level engineering goals. Its mission includes bringing together researchers from diverse industrial, academic, and governmental laboratories whose work can contribute to the development of process safety issues that can have a far-reaching impact on the chemical processing industry. The Center also has the responsibility of outreach to industry, to other universities and educational institutions, and to the public as a whole. A program at the Michigan Technological University bears certain similarities insofar as the educational and research component is concerned. As illustrated by the following discussion, however, the Center programs span not only education and research, but also include training, service, information dissemination, and symposia.

The Center has also recently established a dialogue with the Center for Chemical Process Safety (CCPS) in order to coordinate activities for accomplishing mutually desirable process safety goals. While CCPS also focuses on making an impact on process-safety-related issues, the Center's goals and objectives are much deeper. They include shifting the paradigm to safety being second nature and incorporating process safety into the curriculum. The Center programs and activities are meant to complement and enhance the CCPS efforts. Success toward these goals at Texas A&M University is a first step in this process. Future plans include activities to encourage similar initiatives at other institutions. Based on the availability of funds, these activities could include joint projects or grants to encourage teaching and research in the areas of process safety. The Center is working on several proposals that could lead to joint projects with other universities under grants provided by government agencies.

GOALS OF AN INTEGRATED APPROACH

The first step in accomplishing the goals and objectives from the university perspective is for educators to recognize that process safety should be integrated into a comprehensive instructional and research program. For example, is it appropriate for educators to teach process design courses without adequately covering concepts of inherently safe design and other process safety concepts? Is a course on reaction engineering complete without due treatment of runaway reactions, the causes of such reactions, and what role an engineer might have in preventing them? Finally, offering the opportunity for students to take specific process safety engineering courses is critical in the integrated approach. Research should be directed toward developing safer processes, equipment, procedures, and management strategies that will minimize losses within the processing industry. The goals of an integrated approach span a large spectrum of issues focused toward programs and activities that encourage safety as second nature. The goals cover four broad areas: instruction; information storage, retrieval, and analysis; service; and research. Some of the general goals include

- *Marshaling all the resources of the university that can be applied to process safety and risk management, advertising these capabilities, and bringing these resources together to solve complex problems that require multidisciplinary teams*
- *Developing the capability to respond quickly and effectively to the research needs of other organizations*
- *Attracting outstanding faculty, researchers, practitioners, and students to participate in process safety research programs and activities*
- *Sponsoring or participating in safety-related events such as symposia and design contests*
- *Serving as a role model in good safety practices for other institutions and within the University*

Of these general goals, attracting outstanding faculty, researchers, practitioners, and students is by far the most critical. The extent of the problem is illustrated by the fact that because of industry initiatives and regulatory requirements, process safety engineering and associated technologies have become an essential feature of all chemical processing design and operations. But almost all universities lack effective teaching and research programs to support the needs of industry. This situation can be changed only by putting in motion a cycle that irrevocably changes the paradigm. For example, we could produce several chemical engineering PhDs per year with specialization in process-safety engineering, and they could then go on to teach at other universities or conduct beneficial research in solving process safety problems. Thus, the courses they teach (including classical engineering courses) would contain a comprehensive approach including consideration of all process safety issues. In addition, their research would definitely include the solution of many process safety problems.

EDUCATION

The educational programs of the Center are based on a three-pronged approach. First, to establish a series of undergraduate and graduate courses dedicated specifically to process safety engineering. Second, to act as a catalyst for incorporating process safety problems into existing courses such as design, reaction kinetics, and thermodynamics. Third, to sponsor training of engineering faculty through participation in continuing-education short courses covering process safety. The overall goals in education include

- *Improving knowledge and awareness of process hazards and safety for faculty, students, engineers and other professionals, plant workers, public safety personnel, transportation workers, and the public*
- *Developing state-of-the-art educational tools, undergraduate and graduate courses, and continuing-education programs*
- *Producing engineers with a good education in safety*

The current program of the Center includes an interdisciplinary, elective course in process safety engineering that is cross-listed between chemical engineering and safety engineering programs and has been taught for the last three years. The course is one of the most popular electives in the department. A graduate counterpart of the course has also been developed and taught.

The Center promotes the use of SACHE modules within traditional chemical engineering courses. In addition, to increase faculty awareness, the Center sponsors participation in continuing education short courses on process safety. The intent is to provide information on state-of-the-art safety technologies as well as to encourage faculty to use these courses as opportunities to update process safety elements in the traditional chemical engineering courses. To date, various faculty have attended the following courses:

- *Engineering Design for Process Safety*
- *Tools for Making Acute Risk Decisions*
- *Methods for Sizing Pressure-Relief Valves*
- *Fundamentals for Fire- and Explosion-Hazards Evaluation*
- *Use of HAZOP Studies in Process-Risk Management*
- *Human-Error Evaluation and Human-Reliability Analysis for Chemical Process Systems*
- *Safe Automation of Chemical Processes*
- *Consequences of Vapor Cloud Explosions, Flash Fires, and BLEVEs*
- *Vapor Cloud Dispersion Modeling*

The Center has begun an aggressive program to provide continuing-education courses to practitioners in industry. The intent is to provide training at outreach locations in a format that allows attendees to take the short courses without having to travel long distances and with minimal disruptions in their work schedule. We started with a 13-course syllabus at two campuses: Texas A&M University System Galveston campus and the Texas Engineering Extension Service Pasadena training facility. The courses, taught by both industry and university experts, meet Monday and Tuesday from 8am to 5pm. Continuing education credits are provided for all short courses and attendees may choose to take structured series of courses and receive certificates of attendance for a specific program.

The Center has future plans calling for continued growth and expansion of the efforts already underway. Several advanced-level courses on process safety and associated technologies are being developed. They can be taught by a multidisciplinary team of instructors and offered at multiple campuses through distance-learning technology. Some of the courses under consideration for development include

- *Mechanical integrity of process plants (potential teaming between chemical and mechanical engineering departments)*
- *Advanced topics in safety and environmental management (potential teaming between chemical engineering, industrial engineering, and chemistry departments)*
- *Quantitative risk assessments (potential teaming between chemical engineering, statistics, and business administration departments)*

In the continuing education program, the Center plans to add appropriate courses as necessary, but the ultimate objective is to move from the current campus-oriented offerings to an interactive distance-learning system. Texas A&M University has already implemented distance-learning curricula in the industrial engineering department. The Center intends to collaborate with industrial engineering to develop distance-learning course modules for both graduate courses and continuing education courses.

Within the next few years, MS and PhD graduates in chemical engineering will be finishing their degree programs with emphases in process safety engineering. The degree programs for these graduates will include

- *Traditional core chemical engineering courses*
- *Additional process-safety-specific courses*
- *MS or PhD theses addressing the solution of an engineering problem related to process safety*

INFORMATION STORAGE, RETRIEVAL, AND ANALYSIS

One of the main causes of process safety incidents in the chemical processing industry is the lack of access to necessary information and data. The problem is threefold: first, in many cases the information does not exist; second, even when some information and data are available, accuracy and credibility are questionable; and third, when information exists, it is not well organized or easily accessible. Thus, in the area of information storage, retrieval, and analysis, the Center's goals include

- *Gathering and storing information related to chemical process safety, including case histories, equipment and human reliability*
- *Developing computer databases and user interfaces to provide easy access to and analysis of this information*
- *Analyzing the information and publicizing the results*

The heart of the Center work is its library, which includes books, articles, reports, journals, and other documents focusing on engineering aspects of process safety (*e.g.*, relief systems, dispersion modeling, safe design) as well as the social, economic, and behavioral aspects of process safety incidents and natural disasters. Various software programs are also available. The holdings are cataloged in a computerized bibliographic database. The library catalog is available on-line on the Center website, enabling web browsers to search the library materials for specific publications.

The Center publishes the *Centerline* three times a year. It contains technical and research issues of interest in the field of process safety and risk management. It is also available on the Web site (http://process-safety.tamu.edu/). The site provides information on process safety-issues, publications, and other items of interest for process-safety and risk-management topics. It also allows individuals, companies, and organizations to browse actively and to acquire information on process-safety-related subjects. Access is free and allows the user to conduct interactive searches and provides computations, analyses, and calculations. The site contains information on research, technical papers and reports, access to the library database, regulations, frequently asked questions, access to software, links to other appropriate sites, electronic *Centerline* issues, and announcements for symposia, seminars, and short courses. The site is updated regularly to provide new items and state-of-the-art techniques to users.

Future plans for information storage, retrieval, and analysis include development of computer databases and user interfaces to provide easy access and analysis of process-safety-related information. For example, one item under consideration is development of an incident-history database with fuzzy search capability. This effort can expand to develop an interactive teaching module providing Web-based training. Also, efforts are underway to establish a Process Safety Newsgroup (PSN) that would provide an open forum for exchange of ideas and questions for personnel involved in the process-safety and risk-assessment fields. The purpose of PSN would be to facilitate the exchange of ideas and information among U.S. and international public- and private-sector organizations about prevention of, preparations for, recovery from, and/or mitigation of risk associated with catastrophic accidents in chemical processing facilities.

Another current project is analysis of accident databases to pinpoint specific causes and to determine areas of needed research. The intent is to use the results to determine areas of critical need and to focus efforts on those areas. At this time, the project consists of analyzing portions of the EPA Accidental Release Information Program to develop a strategy of how these databases can be used to improve process safety.

As new information is compiled and research results become available, the Center will disseminate them as widely as possible. In many cases, it may be necessary to publish monographs, research papers, and guidelines. The changing environment and needs of industry dictate, however, that we consider advanced electronic media such as CD-based publications and internet communication.

SERVICE

The mission of a university and its faculty includes providing service to industry and society. The changing nature of the chemical engineering profession necessitates that we take a closer look at how we provide this service. Universities and faculty are remiss if they do not play an adequate role in ensuring public safety. Another issue is that a large number of process plants exist that are either owned by small companies or are so-called "mom-and-pop" operations. An accident from such a small facility has the potential of severe consequences and can damage the whole industry's "license to operate" just as does an accident in a large plant. The larger facility probably has resources, training, and equipment to either prevent the accident in the first place or to respond to the consequences if it does occur, however, while the small facility probably lacks proper awareness, training, and information. Thus, the Center's goals include

- *Providing service to small and medium enterprises, government agencies, institutions, local emergency planning committees, and others to evaluate and minimize risks*
- *Providing independent accident investigation and analysis services to industry and government agencies, particularly for those accidents that suggest new phenomena or complex technologies*

In the area of service to small business, the Center seeks collaborative efforts with government agencies (both state and federal), professional and trade organizations, and industry. Another area of interest for the Center is accident investigation. The Center objective in looking at accidents is fourfold; first, identifying multiple accidents that may exhibit common phenomena; second, finding accidents that suggest new phenomena related to basic research or fundamental issues; third, providing independent third-party evaluation, peer review, or critique of accident investigations conducted by government agencies; and fourth, researching accident investigation techniques and issuing research reports with recommendations for the best possible accident-investigation techniques. Development of software and tools for accident investigation is also an area of interest.

RESEARCH

The overall goals of the research program aim at improving safety in process plants by identifying the greatest risks and then developing inherently safer processes and designs, developing best-practice databases, and solving problems identified by industry. The research goals of the Center include

- *Systematically identifying the greatest risk in terms of severity of consequences and probability of occurrence and prioritizing them*
- *Systematically identifying projects that could be undertaken by the Center and would most effectively address the risks identified by risk analysis*
- *Developing safer process schemes for the most common and most hazardous processes; developing design concepts for implementing such processes*
- *Developing devices, systems, and other means for improving safety of chemical operations, storage, transportation, and use by prevention or mitigation*
- *Improving means for predicting and analyzing the behavior of hazardous chemicals and the systems associated with them*

Current research activities include a reactive systems research and teaching laboratory established for evaluating the reactivity of chemicals and mixtures of chemicals, and to obtain data needed to size relief systems for runaway reactions. A reactive systems screening tool (RSST) exists and operating procedures have been prepared based on two base-case runaway reactions: methanol and acetic anhydride (tempered) and hydrogen peroxide (gassy). The RSST studies can be used for initial reactivity characterization and vent sizing, as well as for a laboratory experiment in the undergraduate unit operations laboratory.

Another research project underway is "Two-Phase Viscous Flow Through Safety Relief Valves." Phase I of the project includes a survey of the literature and evaluation of state-of-the-art procedures for relief-valve sizing in two-phase flow, verification of various theoretical models by experimental data, and recommendation of design practices for viscous two-phase flow through safety-relief valves. Phase II involves experimental design for Phase III, which is the experimental phase. The program includes CFD numerical computation and prediction of two-phase flow through safety relief-valves.

Other research includes "Post-Release Transport and Fate of Toxic Chemicals and Their Mixtures." The objective is to develop mathematical models that accurately represent the transport and fate of chemicals as well as their mixtures resulting from process-plant accidents. Some computer models are available that can be used to make these calculations, but many problems are associated with their application, including problems in handling polar substances and mixtures. Our objective in conducting this research is to address this problem and to develop an approach that can be applied consistently and uniformly.

Future plans for research include establishment of a state-of-the-art reactive chemicals laboratory. The Center has acquired and installed an Automatic Pressure Tracking Adiabatic Calorimeter (APTAC) for reactive screening of chemical reaction compounds and mixtures. The APTAC can be used for thermal analysis of solid or liquid chemicals or for gas/liquid, liquid/liquid, gas/solid, and liquid/solid mixtures. It can obtain time-dependent kinetic data and temperature and pressure profiles for both open and closed systems. It can also be used for process simulation of batch and semi-batch reactions, fire exposures, emergency relief venting, and physical-properties measurement. The resulting information can identify potential hazards and tackle key elements of process safety design such as emergency relief systems, effluent handling, process optimization, and thermal stability.

The Center Steering Committee from time to time evaluates proposals and ideas regarding future research projects. Depending on the situation, funding for these projects is sought from external sources or from internal Center funds. For example, some of the projects currently under consideration are

- *Corrosion-induced fatigue failure for moving parts (correlation between corrosion rates, failure frequency, and intensity of movement)*
- *Methodologies on inherent process safety*
- *Comprehensive database for equipment and component failure rates in the chemical industry*
- *Incident history database*
- *Data integrity and compilation during engineering projects*
- *Human factors research*
- *Thermodynamic data for specific mixtures (e.g., 30% oleum)*
- *Flammability limits and explosivity limits (both experimental and correlation)*
- *Use of computational fluid dynamics to evaluate damage to facilities based on knowledge of gas concentrations in cloud, confinement, and dynamic response of structures*
- *Passive explosive suppression in compartments for offshore structures*
- *Safety protective data and linkage with fire-school activities*
- *Fire suppression with environmentally friendly chlorofluorocarbons*

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Through positive intervention in encouraging reconciliation between courses, we may avoid the ill effects of compartmentalizing courses and help integrate the acquired knowledge of our discipline. Research on cooperative learning is summed up succinctly by Wells, et al.:[7] "...to achieve most effectively the educational goal of knowledge construction, schools and classrooms need to become communities of literate thinkers engaged in collaborative enquiries."

REFERENCES

1. Aronson, E., *The Jigsaw Classroom,* Sage, Beverly Hills, CA (1978)
2. Doise, W., and G. Mugny, *The Social Development of Intellect,* Pergamon Press, New York, NY (1984)
3. Johnson, D.W., *Educational Researcher,* **10**, 5 (1981)
4. McInnis, C., R. James, and C. McNaught, *First Year on Campus,* Australian Government Publishing Service, Canberra, Australia (1995)
5. Dalziel, J.R., and M. Peat, in *Improving Learning,* C. Rust, ed., p. 272, Oxford Centre for Staff and Learning Development, Oxford (1998)
6. Ausubel, D.P., J.D. Novak, and H. Hanesian, *Educational Psychology: A Cognitive View,* Holt, Rinehart, and Winston, New York, NY (1978)
7. Wells, G., G.L.M. Chang, and A. Maher, in *Cooperative Learning: Theory and Research,* S. Sharan, ed., p. 1, Praeger, New York, NY (1992) ❐

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- *Best-practice databases (e.g., for an ethylene plant, what controls, procedures, and training are adequate)*
- *Methodology to determine time-concentration effects of various toxic materials and combination of these materials*
- *Computational methods for determining fire resistance of structural components in process facilities*

IDENTIFYING PROBLEMS AND MULTIDISCIPLINARY APPROACH

Universities solve problems identified by researchers or industry. For an applied engineering field such as process safety engineering, the problems are usually identified by industry. The approach is to develop effective mechanisms for getting industry input and then taking a multidisciplinary approach to solve the problem. To address the latter, the Center has assembled a highly qualified team of experts who have international reputations in fields ranging across reaction engineering, inherently safe design, numerical analysis, system and equipment reliability, applied probability, organizational structure and planning, non-destructive evaluation, experimental fracture mechanics, materials testing, risk assessment, exposure assessment, cost-benefit analysis, and other areas of expertise.

The vehicle used to identify problems is based on two factors: first, the Center actively seeks input from industry in identifying process safety engineering problems that the Center can help solve, and second, an annual symposium "Beyond Regulatory Compliance: Making Safety Second Nature" is a vehicle to generate ideas and to identify problems.

CONCLUSIONS

In response to the changing role of chemical engineering, chemical engineering departments must adjust and modify their approach to education and research. The education must include a comprehensive exposure to core courses integrated with process-safety problems as well as a limited number of specific process safety engineering courses. Chemical engineering departments must also produce an appropriate number of MS and PhD graduates whose degree programs are focused on process safety engineering problems. Also, to help our graduate students transition into industry, the research we conduct should help industry in a practical and immediate manner. This can be ensured by seeking adequate input from industry as well as other stakeholders.

Public perception of the process industry is significantly affected by process plant accidents. The significant societal role played by industry is largely overlooked when catastrophic accidents occur. The best way to change that perception is through adoption of proactive programs by both industry and universities.

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REFERENCES

1. *Accidental Release Information Program,* US Environmental Protection Agency, Washington DC (1989)
2. *A Review of Federal Authorities for Hazardous Materials Accident Safety: Report to Congress Section 112(r)(10) Clean Air Act as Amended,* US Environmental Protection Agency, Washington, DC (1993)
3. *Accidents Do Happen: Toxic Chemical Accident Patterns in the United States,* National Environmental Law Center and United States Public Interest Research Group, Washington, DC (1994)
4. *Toxic Chemical Release Reporting, Community Right-to-Know,* Code of Federal Register, 40 CFR 372, US Environmental Protection Agency, Washington, DC (1991)
5. *Guidelines for Engineering Design for Process Safety,* Center for Chemical Process Safety, American Institute of Chemical Engineers, New York, NY (1993)
6. Kletz, T., *Lessons from Disaster: How Organizations Have No Memory and Accidents Recur,* Gulf Publishing Company, Houston, TX (1993)
7. Kletz, T., *Learning From Accidents in Industry,* Butterworths, London, UK (1988) ❐