risk analysis

technology

inherently safer design

process safety

Process Safety Research Agenda for the 21st Century

safety culture

resilience engineering

hazardous phenomena

PROCESS SAFETY RESEARCH AGENDA FOR THE 21st CENTURY

A policy document developed by a representation of the global process safety academia

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TABLE OF CONTENTS

Executive Summary

Process safety is a relatively young and evolving field largely – and unfortunately – advanced by tragic events that, ironically, underscore the importance of the field only after the fact. Even today, in light of many serious industrial incidents and the resulting losses of property and life, a disturbing school of thought exists: if nothing bad happens, it is because there are no hazards, and if there are no hazards, then there is no need to take preventive measures.

Yet another obstacle to effective and proactive process safety efforts is the prevalence of cost-cutting measures adopted throughout industry during a time when operations are increasing in complexity and overall human education/experience has decreased.

In short, the risk remains for serious and significant industrial incidents, and to make further progress towards the prevention and mitigation of such incidents, a deeper examination of their root problems is necessary. The simple things have been discovered and applied, but complexities remain in science and technology as well as in organization. Through the utilization of science and engineering, researchers and practitioners have the potential to address these complexities and achieve advancements that prove useful to the implementation of effective process safety.

With that in mind, the Texas A&M University System Mary Kay O'Connor Process Safety Center convened in 2011 an unprecedented gathering of academicians from around the world to develop, "Process Safety Research Agenda for the 21st Century."

During the deliberations, 19 areas were identified to focus future research: hazardous phenomena; inherently safer design; risk management; consequence analysis; critical infrastructure protection; complex systems; resilience engineering; integration of process safety with occupational safety; organizational/human factors: distinguish between technology and people; safety culture; mechanism to import process safety into emerging technologies; safety technologies; layers of protection, mitigation system; life cycle/maintenance; process safety management knowledge: transfer, improved access; dissemination; standardization of process safety methods; integration of databases for improvement of process safety; easy-to-implement process safety methods for the industry; application of process safety to drilling operations; and natural hazard triggering technological disasters (NaTech).

Efforts were made to further categorize this list in terms of technical and organizational initiatives, recognizing that the list needs to be prioritized in terms of a set of criteria. To that end, and recognizing the need to pursue and fund these areas on a global basis, formation of a global process safety organization was proposed. The coordinating role of this group was developed, including potential categories of members, e.g., multinational companies, international organizations and governments. To initiate this work, the panel asked that Professor M. Sam Mannan and the Mary Kay O'Connor Process Safety group scope out the effort, including initial members, proposed research and budget. A second workshop should then be held to review and further develop plans for this internationally focused organization.

Introduction

Perhaps more so than any other field, process safety suffers from a widespread neglect rooted in a false sense of security. Specifically, the importance of process safety typically becomes evident and emphasized only after negative events have taken place, and losses of property and life have occurred.

The post-event response to "Y2K," the millennium bug, is a prime example of this human denial that characterizes a larger, problematic social attitude. Shortly after the beginning of the year 2000, the worldwide effort to prevent and diminish the expected computer systems problems associated with the turn of the century was bitterly criticized. Providing endless fodder for late-night comedians and various talking heads, this proactive measure was portrayed as an unnecessary overreaction because, ultimately, nothing of significant consequence occurred.

In the case of process safety, the debate and the cost of doing nothing is much sharper and in focus. With that in mind, the Mary Kay O'Connor Process Safety Center (MKOPSC) was established in 1995 in memory of Mary Kay O'Connor, an operations superintendent killed in an explosion on Oct. 23, 1989 at the Phillips Petroleum Complex in Pasadena, Texas. Mary Kay O'Connor graduated from the University of Missouri-Columbia with a degree in chemical engineering and received a Master of Business Administration from the University of Houston-Clear Lake.

The mission of MKOPSC is to promote "safety as second nature" in industry throughout the world with the goal of preventing future accidents. In addition, MKOPSC develops safer processes, equipment, procedures and management strategies to minimize losses within the processing industry. MKOPSC recognizes that it is necessary to advance process safety technologies in order to keep the industry competitive. Other functions of the center include that it serves all stakeholders, provides a common forum, and develops programs and activities that will forever change the paradigm of process safety. The funding for the center comes from a combination of its endowment, consortium funding and contract projects.

In keeping with its mission, MKOPSC annually sponsors the "International Symposium: Beyond Regulatory Compliance, Making Safety Second Nature" in College Station, Texas. The 2011 symposium was held Oct. 25-27. Prior to the symposium, on Oct. 21-22, a distinguished panel of select process safety experts was convened to participate in the "Workshop on Process Safety Research Agenda for the 21st Century" with the intent of preparing a roadmap for process safety in the next century. Dr. M. Sam Mannan served as chair of the panel. The vice chairs of the panel were Dr. Hans Pasman, Dr. Richart Vasquez-Roman, Dr. Ray Mentzer, Dr. Venkat Venkatasubramanian, Dr. Paul Amyotte and Dr. Jose Torero. Biographical sketches for each of these panelists can be found in this report.

Unfortunately, numerous incidents throughout the world continue to underscore the need for better engineering and design; more effective management systems; and improved technology and advances in behavioral safety and safety culture. Given this compelling truth, the questions posed to the participants of this unprecedented workshop were, "What process safety issues need to be addressed by research, and what role do academic organizations have in teaching process safety to new generations?" The latter forms a process onto itself, which unfortunately requires years of development – from even a mature student – to achieve a comprehensive understanding and the critical, independent thinking skills necessary. For the conducting of research concurrent with education, it is vital to address the needed funding mechanisms and how networking and teaming opportunities can be used to further these causes.

Process safety concerns the avoidance of incidental mishaps in various kinds of continuous, semi-continuous or batch industrial processes in which substances are released that are hazardous themselves or in combination and after mixing with air. These hazards when uncontrolled can lead to various adverse consequences on people, neighboring structures and the environment at large. The effects of the unintended and, in some case, intentional (e.g., terrorism) release of a hazardous substance/material can be explosion blast and debris, flame and fire, and toxic load. The latter can result from the released substance directly as well as products of combustion or by denying normal life-enabling conditions, such as asphyxiation from lack of oxygen. To be distinguished from process safety but related to it, are human protective measures to avoid injury or death of personnel. These measures are clustered under the term "personal safety."

Processes are many and in large varieties. The generation of energy by combustion processes as well as the manufacture of substances/materials on an industrial scale from other materials by a chemical process or by separating components of a material and refining or purifying them encompass all operations. Hence, most of these industrial processes are known as the chemical industry, but the chemical industry also includes the huge gas and oil industry and power-generating plants. Generally, the process safety community does not include the safety experts of nuclear power plants, although both have much in common, and many of the methods and concepts in process safety find their origin in safely handling the nuclear processes.

On the other hand, process safety is applied to the storage of hazardous materials and the transportation of those materials on road, rail, water and in air. Given this, the safety issues related to the entire system of exploring, mining, refining, producing, transporting and storing of substances/materials with hazardous properties or under hazardous conditions will be considered. In addition, safety in academic institutions also presents significant concerns. In these facilities, explosion, flammability and related tests are carried out, and nano-materials are synthesized. This has become a great concern for process safety.

Various distinctions exist in the broad field of process safety. These are pure chemical, physico-chemical, physical, thermodynamic, statistical, systemic, medical, psychological, sociological and ethical aspects but also aspects of process technology and engineering, management, economy and organization – some being more important and far reaching than others. Safety is supported by data and multipurpose process models that come from diverse areas such as design, science and engineering, as displayed in Figure 1.

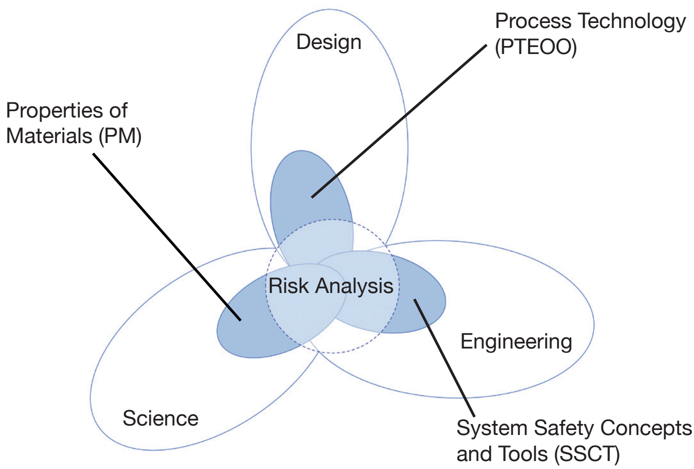

Figure 1: Process safety fields against a background of science, design and engineering; the circle in the center represents risk analysis methodology. This figure concept is inspired from a knowledge infrastructure paper of the Dutch Advisory Council on Hazardous Substances, 2008.

Properties of materials (PM) is a well-defined area from which the hazards of substances originate. Another area that process safety shares with other safety expertise in technology and engineering is that of system safety concepts and tools (SSCT) while a third area is more specific to the type of operations mentioned earlier: process technology, engineering, operation and organization (PTEOO). These three fields neighbor each other or overlap. Because process safety targets avoiding damage due to the loss of containment of hazardous substances, it is essential to predict such potentially disastrous scenarios, the degree and extent of the damage associated with a scenario, and the measures necessary to prevent and to protect against such scenarios. Hence, the ability to imagine all aspects of such a scenario is crucial. This includes understanding all possibilities by which a process can derail as well as the probability and consequence of each scenario. In other words, the risks involved must be predicted. The field of risk analysis therefore encompasses the three fields previously mentioned (PM, SSCT and PTEOO) as an umbrella with its own methods and tools. Figure 1 illustrates these fields against the background of science, design and engineering.

Below each field is described in more detail:

A. Properties of materials

The hazard presented by a substance or a mixture is its capability to start reacting unintentionally and generating heat, and/or its toxic, pungent or corrosive effect on people or the environment. The exothermic reaction of a substance can be the result of an ignition or the result of self-heating after it reaches a sufficiently high temperature. Ignition sources are usually abundant. Self-heating of a (reactive chemical) mass of liquid or solid substance as a net result of production of heat of decomposition or reaction and of rate of cooling is called runaway. In many cases a flammable substance becomes a hazard after it has mixed with air. Also, reaction can then start upon ignition or by self-heating. The dynamics of these processes are important; the dynamics are determined by the kinetics of the chemistry (rate of reaction increases with temperature – thermal explosion) and partly by the physics of propagation of a reaction zone (deflagration: thermal, or detonation: compression). The higher the energy release rates involved, the stronger compressive effects by the generation of shock waves and the throw of fragments. Damage is also due to spread of hot gases and toxic products. For some substances, decomposition products are much more hazardous than the original substance or mixture. The field is concerned with development of test methods; investigation of mechanisms; interpretation of test results; development of safety standards; and prescription of packaging and handling.

Much experimental work has been conducted to evaluate calorimetric properties of substances such as thermal decompositions (e.g., Saenz et al., 2011). The analysis of the ability to estimate the heat release rate of energetic materials indicates that corrections are required in all calorimetric methodologies (Biteau et al., 2009). Among other properties, detonation characteristics of condensed substances must be better understood (Miyake et al., 2007).

For gas explosions the theoretical basis for the flammability limits is still rather thin, certainly for the upper limit, which impedes prediction. Experiments therefore continue to be necessary, which for mixtures forms a burden. Of various liquids the flammability envelope has been experimentally determined up to the point of vapor saturation (e.g., Brooks and Crowl, 2007). Knowledge at other-than-ambient conditions is still scarce.

In recent years, the modeling of dust explosions in complex geometries via CFD-code appears possible (Skjold et al., 2006), but much work remains desired since the fundamentals of dust deflagration mechanism are not yet fully understood.

Many of the methods in this field are borrowed from reliability engineering with its statistics to process failure data of technical parts and to predict failure rates and their distributions. A major aspect of prediction is uncertainty analysis to provide confidence limits of a finding. Reliability engineering also regards the prediction of failure of systems composed of components and sub-systems by means of fault tree analysis. A special part is human reliability analysis. Knowledge of failure modes in turn provides incentives to develop constructions and arrangements that are fail-safe. It also led to the first probabilistic standard: the IEC 61508 (specific for process industry IEC 61511) that was developed in the second half of the 1990s. This was the result of the possibility of high confidence prediction of very low failure rates of electronic components and circuitry. It provided a reliable guarantee of the functioning of protection devices (systems consisting of sensor, processor and actuator) with a specified reliability level. Because the statistics are mathematically intensive in this field, the availability of simulation methods became quite useful.

B. Process technology, engineering, operation and organization

This again is a broad field in itself; it comprises technology and organization. Both technology and engineering are concerned with inherently safer design solutions of processes, components, equipment and installations as a whole. Here, trade-offs of safety improvements versus process economy become a major factor. Also, appropriate knowledge about substance properties; behavior under process conditions; and adequate computer simulation methods of processes are keys to reliable prediction of safe operation. A major step in the 1990s has been the introduction of safety management systems as a tool to increase operational safety. Such systems are based on a vision of safety at the top of the organization and condensed into a safety policy statement. Related procedures are then developed, reviewed at fixed times and improved. A safety management system comprises a number of elements such as accountability (tasks and responsibilities), process documentation and knowledge, personnel qualification and training, occupational safety measures, review procedures and management of change, incident investigation and risk management, integrity of equipment with inspection and maintenance, compliance with regulation, standards and codes, and audits. Lately, attention to safety attitude and safety culture; involvement of work force; and stakeholder outreach also has been intensified.

There exists a significantly large number of physical models that when put together might generate a large uncertainty. This uncertainty could be so high that the analysis and decisions taken based on this information may be seriously flawed. Thus, the engineering and technological basis for risk analysis should include the further development of models and more cautious use of simulators.

C. Risk analysis

Risk analysis makes use of information generated in all three fields above and, in addition, shares knowledge with risk analysts in the many other fields of technology. In process safety it begins with Process Hazards Analysis (PHA). Several methods have been developed and applied for scenario generation such as Hazard and Operability (HAZOP) analysis; Failure Mode and Effect Analysis (FMEA); use of incident data banks; Fault Tree Analysis (FTA); and Event Tree analysis (ETA). In the last decade, major improvements have been made by combining FTA and ETA into a "bow tie" with the critical hazardous substance spill event as the top event of the fault tree and the base event of the event tree. These bow ties also show the locations of the preventive and protective measures. With regard to the latter, a tool that has spread quickly is Layers of Protection Analysis (LOPA), which is based on an event tree and provides insight into the reliability of protective measures. Quantitative risk analysis has been in use since the early 1980s and is applied a great deal in tackling land use planning problems. It consists of physical effect calculations such as release rates, evaporation rates, dispersion of cloud, radiant heat calculation of various types of fires, effects of explosion, probability estimates of injury and death of people and damage to structures and environment. It presents the risks of an operation in various forms such as expected frequencies of exceeding a number of fatalities; also as (individual) fatality risk contours on geographical maps; or as overall expected losses. Problems involved are uncertainties in scenarios, data and models, which may result in order of magnitude uncertainty in final results. Developments on many aspects continue, and some examples are given below.

The concepts and implications of the thermodynamic and mechanical effects on the behavior of flashing jets that might produce explosions or fires have been reviewed recently by Polanco et al. (2010). Dispersion models essential to the consequence part of risk analysis develop these concepts further. For example, a Gaussian-type (solid particle) aerosol dispersion model has been used to assess the stochastic impact distances for particles larger than 0.1 μm (Godoy et al., 2009). The depth of perforation produced from metallic projectile impacts has been analyzed (Mebarki et al., 2007). This model has been implemented to extend the capabilities of STRRAP, a prototype package developed to estimate the mass concentration distributions and impact distances of explosion debris (Godoy et al., 2007). The gas dispersion that produces an explosion has been simulated using a CFD-based model (Tauseef et al., 2011).

A knowledge-based system has been developed to integrate qualitative and quantitative process models in the form of HAZOP tables (Németh et al., 2005). A decision-support system based on neural networks called NAROAS is used to computerize reliability monitoring of a nuclear power plant (Gromann de Araujo Góes et al., 2005). Genetic algorithms have been used to produce optimal layouts of chemical facilities (Castell et al., 1998). A knowledge engineering framework has been developed to aid experts in conducting HAZOP analysis (Zhao et al., 2005).

A review of the most important advances in the assessment of fire safety is contained in Williamson and Dembsey (1993). A total of 62 methodologies to undertake risk analysis have been identified and distributed into three phases: identification, evaluation and hierarchisation (Tixier et al., 2002). Bayesian theory has been used to forecast risk based on incident databases (Meel et al., 2007). A security risk factor table and a stepped matrix procedure have been proposed to assess security risk in the oil and gas industry (Srivastava and Gupta, 2010). It is argued that risk in process industries can be substantially inherently reduced by improving layouts (Vázquez-Román et al., 2010). LOPA also has been successfully applied in the process industry (e.g., Markowski and Mannan, 2010).

What Achievements Have Been Made in Process Safety and Where are the Open Ends

Fifty years ago process incidents were not uncommon, to say the least. Investigations were primarily concerned with how such incidents could take place, largely because phenomena such as "vapor cloud explosion" or "runaway" were not yet defined. After several catastrophic incidents the significance of static electricity was recognized in igniting flammable mixtures. In many incidents in which human fault/error could have been the most relevant cause – and although the operator could have justifiably been terminated – improvement was sought in more reliable equipment. Later in the 1980s human factors were recognized as important, and improvements were made through behavioral science. Later it became clear that management plays a key role in achieving an effective level of safety, and the introduction of safety management systems followed. Last but not least, a recognition and emphasis on the role of safety culture emerged.

This evolution is illustrated in Figure 2.

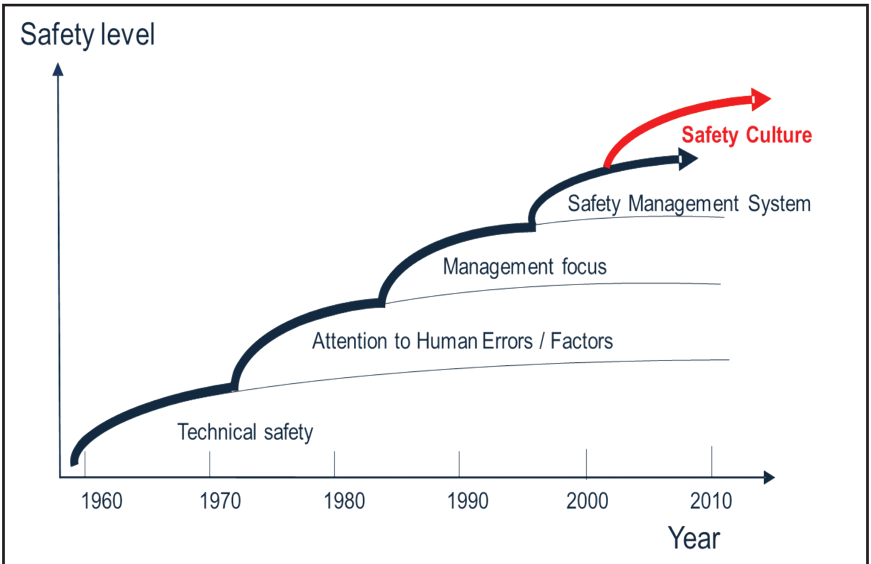

Figure 2. Various contributing factors to process safety throughout the last 50 years.

An important driving force in safety improvement efforts has been the drafting of regulations both in the United States and Europe, mostly initiated after disastrous incidents have occurred. These regulations have developed along two lines: protection of workers in plants (Occupational Safety and Health Administration) and protection of populations on or near related sites (Environmental Protection Agency). While such regulations are important, they should be viewed as the minimum standard with the recognition that regulations alone cannot improve process safety performance.

The body of process safety knowledge has grown impressively throughout the years. Following the 1984 Bhopal disaster, there has been increased activity in the research and academic communities related to process safety in the chemical industry. The increased activity is illustrated in Figure 3, which lists (through the year 2002) the total publications in science and engineering journals that mention "process safety" as a keyword. The articles detail a wide variety of safety topics, ranging from clinical studies to estimate toxicity; risk management; design and manufacturing processes; and environmental and regulatory issues.

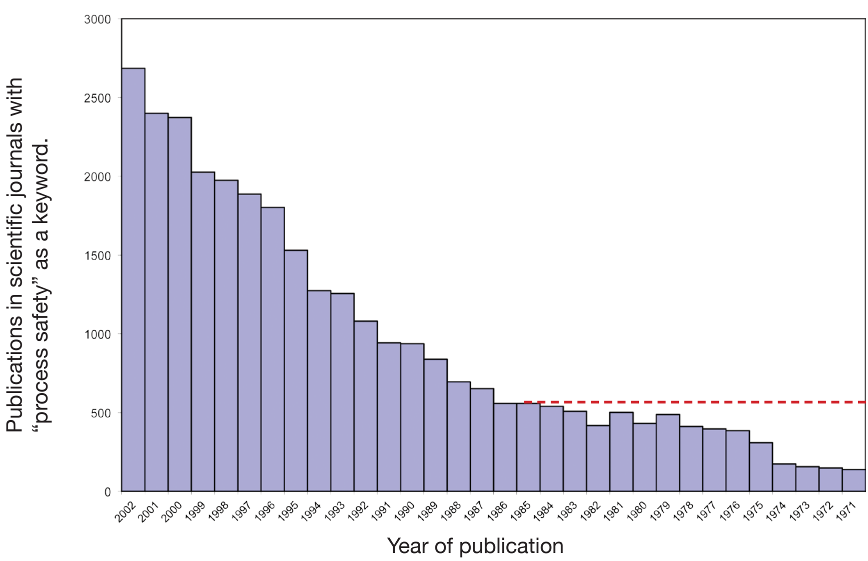

Figure 3: Publications in science and engineering journals that mention "process safety" as a keyword. The dashed line signifies the pre-Bhopal period (reproduced with permission from Elsevier, Inc.).

In several countries long-term research efforts have been undertaken. For example, in the United States and Europe government funds have been made available to investigate hazardous phenomena and to develop and evaluate test methods and computational tools. In addition, a series of loss prevention symposia started in the United States in the 1960s and found a parallel in Europe in the 1970s. Process safety symposia were later organized in Asia. Specifically in the United States, MKOPSC has since 1998 sponsored and organized a well-attended annual international symposium.

Although significant progress in process safety has been made through these and other related efforts, there still appears to be many "open ends" in the existing knowledge. For process safety researchers it is abundantly clear that further development of this knowledge base is needed due to the complex nature of the field and the myriad ways in which things can go wrong.

To state that a situation is 100-percent safe has proven many times to be a gross exaggeration with serious consequences. All test methods and models have limitations. Compounding this issue are highly complex, individualized scenarios and a widely varying human fallibility factor.

The effects of this knowledge gap are evident; even today, reliable data for examples on failure rates are scarce. The variability between installations is large, and imagining and describing scenarios often proves insufficient. Post-incident investigations often have led to questions pertaining to why certain scenarios were overlooked during the PHA or why certain technology was not implemented. In particular, management effectiveness and human reliability are difficult to establish. There is not yet much experience in defining and monitoring indicative process safety performance indicators. On the other hand, since the 1970s, personnel safety incidents for most industrialized countries – expressed as "work time lost" – show a steady downward trend. Placing too much emphasis in the downward trend of this metric, many in industry management, in the late 1990s, inferred that process safety incidents were also decreasing.

As previously mentioned, process safety has many aspects with ties to a large variety of disciplines. Effective safety begins with reliable process modeling; greater knowledge will therefore be beneficial and have a positive impact on approaches and methods. Particular fields of interest include:

A. Computing, instrumentation

Due to the complexities in flow and mixing processes and because of a dependence on simulations to make reliable predictions of the effects of dispersions of cloud, explosion and fire in a detailed environment and in a realistic way, process safety can make use of further developments in computational fluid dynamics (CFD), a field practiced in various engineering departments. For example, this is true for Large Eddy Simulation. Also, inclusion of chemical kinetics in reactive flow will greatly help in determining such things as explosion limits. For gas explosions, detailed kinetics have become available, but their inclusion in CFD is still limited due to the computational capacity required. Simulating dust explosions is still a challenge, but such tools can help design suitable safeguarding measures.

Another computing-related branch of interest is electronic and molecular structure modeling to determine chemical reactivity of substances. Such tools are becoming increasingly prevalent in chemistry departments throughout the nation.

Instrumentation is crucial for reliable testing and revealing more details. Development of such instrumentation is largely the domain of small businesses. Specialized optical diagnosis instrumentation, as in combustion research, will assist in investigating gas, dust and aerosol explosions.

B. Statistics and reliability engineering

With regard to statistics, the longstanding debate between “frequentists” and “Bayesians” is beginning to favor the latter. In the last few years much work in Bayesian data processing and in Bayesian Belief Nets for inference, diagnosis and decision support has produced practical software. This software will greatly reduce if not remove the computational burden associated with Bayesian data processing, making the approach more accessible and potentially providing the risk analysis field with new process safety tools.

Furthermore, reliability engineering is already a robust and mature discipline, and process safety researchers could learn more from findings in that field as they seek to make optimized decisions.

C. Psychology and organizational science

After having previously focused on individual human capacity to commit errors and mistakes, attention in this aspect of the field has since shifted towards study of the whole, examining the processes in a crew and a workforce to determine the quality of the final result. Present key words include "resilience engineering" and "safety culture." Both concepts are useful in assessing a situation as well as examining a scenario in hindsight in order to develop an explanation for incidents.

D. Construction design and engineering

Safe design must effectively account for potentially highly dynamic phenomena and peak impacts such as those that occur in explosions. This also has a bearing on the loading of structures and the behavior of materials under dynamic stresses. Advances in finite element codes developed for mechanical engineering and material science hold promise. For decision-making, a probabilistic approach is favorable.

E. Process equipment, systems and control

In chemical engineering, advances in hardware will have an impact on process safety. Focus on systems is centered on optimization for improving efficiency and saving energy by combining unit operations such as extractive distillation; by reducing by-products and solvents; and by intensifying conditions – not only by temperature, pressure and catalysts but also by using gravitational, acoustic, magnetic and electro-magnetic forces (UV and microwaves). Further automation of control is supporting this. Inherent safety and sustainability drivers should contribute to orient this process, to improve process safety and to avoid risk trade-offs.

Process industry has expanded tremendously worldwide throughout the last 50 years. Oil has been the raw material for an extensive petrochemical industry that produces materials for the products without which life on earth would be poor if not impossible. Catalyst and reactor technology as well as novel control and separation technology has created a large spectrum of possibilities. The process industry generates power and produces fertilizers, fuels for heating and for enabling mobility, construction materials and textile fibers. It enables food processing, waste removal and supplies of drinking water. In general, experience has increased and safety levels have improved each year. By the end of the 1980s, the chemical industry associations started the "Responsible Care" program to focus their efforts on curbing pollution and enhancing safety. The multinational companies are leading the effort. In the United States and Europe process safety centers have been founded by professional engineer associations with the intent of advancing safety methods and techniques.

To help predict the future, it is important to inspect the past, chiefly asking if progress has been made and what elements remains (Pasman, 2009). The validity of quantitative risk analysis (QRA) also has been debated, with opponents arguing it should be replaced by other simplified methodologies since risk cannot adequately be described by summarizing probabilities and expected values; the need for seeing beyond the standard probabilistic risk results of a QRA remains (Aven, 2008). Learning from the past may improve by examining the assumptions and paradigms underlying safety engineering (Leveson, 2011a). Reniers and Amyotte (2011) analyze future trends in managing prevention within chemical industries. The regulatory initiative REACH that includes applications of ab initio techniques to generate predictions of key properties of broad classes of chemicals has been analyzed in Lewis et al. (2007).

Information required to evaluate available investment options in prevention and protection is still lacking, as appears in protecting against domino effects as formulated according to the requirements following from game theory (Reniers, 2010). An index to evaluate the domino potential hazard includes the effect of inherent and passive protection measures (Tugnoli et al., 2008). The possibility of domino effects produced by projectiles generated by explosions in industrial facilities has been analyzed (Nguyen et al., 2009). An approach to quantitative risk assessment of incidents caused by domino effect was developed, also proposing a simplified model for the estimation of escalation probability caused by fire (Cozzani et al., 2005, Landucci et al., 2009). Inherent safety approaches can prevent the escalation of events leading to domino effects (Cozzani et al., 2009). The analysis of 225 domino effects that occurred in process plants or during the transportation of dangerous materials indicates that the most frequent causes are external events and mechanical failures (Darbra et al., 2010).

In addition, another confounding factor that may contribute to an increase in the frequency of incidents is the trend of the process industry to migrate to developing countries where safety and environmental regulations may be less severe. Another aspect of process operations in the 21st Century is the increased use of specialized contractors, but it is not clear how these contractors, their products and their services are managed within the operation of an organization. This aspect might generate deviations from previous risk analysis of a facility or operation. The way in which contractors are managed might completely change considerations regarding operations, which could appear "external" to the organization. This could lead to lack in the flexibility of control and robustness of standards for managing contractors. Thus, contractor risk management is highly important.

The cause-effect behavior of process systems can be captured in a signed digraph where unsafe factors are easily identified (Wang et al., 2008). This technique is related to other digraph-based ones such as fault and event tree and Bayesian Belief Nets.

An emergency response system for hazardous gas releases has been developed where a modified SLAB model uses sensor data to predict gas dispersion (So et al., 2008). Emergency response procedures in semiconductor plants are reviewed to reduce loss in Taiwan (Lin et al., 2009). There remains much room for further improvement, and industry can more effectively apply its resources for safety investments if additional information becomes available.

Despite the immense benefits of the process industry for society as a whole, the tolerance level of the public at large for the risks and the miscues of the process industry has not increased. On the contrary, a mishap with effects "outside the fence" can lead to the dismantling of a plant. At the very least, there will be pressure on the company to introduce expensive, additional safety measures. Acceptability is a matter of trust. The public and hence the authorities and regulators do not want to be surprised by new, potentially large risks and incidents. In keeping with that, once negotiation on a license has been finished on the basis of a risk assessment, there should be no doubts later arising on that assessment. Also, the public cannot cope with large uncertainty as well as the potential of severe consequences no matter how small their probabilities. Often, conflicting interests result in the cancellation of projects when risk analysts supporting the project developer believe the risks are within the limits of tolerability while other scientists with the same strength of arguments state the risks are outside the limits of tolerability.

Throughout the last 20 years – and due to increasing production capacity and globalization of trade – competition has been on the rise while returns on investment have decreased. This has created pressure on management everywhere to reduce costs (see, e.g., Knegtering and Pasman, 2009):

A. In the 1990s cost cutting led to extensive downsizing in all areas, including process safety expertise. Reduction of staff has occurred while workload has continued to grow. Concurrently, due to changes in attitude and opinion on career planning, "job hopping" has increased with all associated aspects, resulting in loss of process-specific experience and involvement. Outsourcing of tasks to small, specialized enterprises and focus on core business shifted from the exception to the norm. This has resulted in loss of communication quality. What's more, early retirement has become almost standard, further resulting in "brain drain" and loss of experience.

B. Complexity of process installations has increased because of the drive for energy savings, higher process flexibility, and better product quality while installations themselves are increasingly pushed to operating limits – all in the name of obtaining the best efficiency and returns.

C. Also, process control and safeguarding equipment has become more complex, allowing flexibility and overview on a higher level. This has led to operators managing the installation instead of controlling flows and reacting to alarms. Related drawbacks are an increasing risk of faulty use of equipment and less direct contact to the hardware. Literally, operators can no longer smell if something goes awry.

Despite increased knowledge regarding the nature and causes of process incidents, the previously mentioned factors can contribute to the deterioration of an environment in which safety can prosper. The vapor cloud explosion at the isomerization unit of the BP Texas City refinery in March 2005 that resulted in 15 fatalities due to overfilling a column with hydrocarbons and subsequent discharge into the air triggered a thorough investigation, first by the U.S. Chemical Safety and Hazard Investigation Board and later by the BP U.S. Refineries independent safety review panel under the chairmanship of James A. Baker III, former Secretary of State. This investigation uncovered the management failures and lack of safety culture that led to the disaster. Other tremendously costly incidents as well as the Deepwater Horizon disaster have demonstrated the same trends. In hindsight, no new mechanisms or unknown hazards have been revealed. Unfortunately, knowledge about the risks involved has been available, but at the crucial moments of decision-making it is either not present, or it is ignored because of other pressures. At the very least, the decision made in absence of this information narrows the safety margin so that with a series of these kinds of decisions, the processes or operations reach a significantly higher level of risk.

The drive for maximum efficiency, which often accompanies efforts to minimize operating time, remains a prevalent mindset. This can easily lead to cutting corners with respect to safety measures; such actions may avoid negative results but produce few positive effects. This trend has triggered a counter-movement in which new measures are developed and a strengthening of the safety management system has been proposed. “Safety culture” and “risk-based process safety” have become new keywords.

Other trends include the development of new processes. In part, this is due to a shift in fuel types as a result of the desired improvement in the sustainability and the reduction of carbon dioxide. The oil-based industry is expected to slowly change into a natural gas-based one, and the use of hydrogen as an energy carrier/fuel also can be expected. Certainly hydrogen – an element with properties that have been known for a long time despite its lack of large-scale use – requires a more stringent safety regime than do liquid hydrocarbons. Removal of carbon dioxide from combustion products and sub-soil storage of carbon dioxide also will introduce new hazards.

Process intensification and the production of nano-materials are two more trends. The former is believed to be inherently safer than conventional processes. Although this is partially true with respect to reactors in which hold-up of reactants is minimal, large-scale adaptation will result in the same problems encountered with separation processes and storage.

Nano-materials form a new area that requires significant consideration. Because of the variability of material properties on molecular scale and the unknown ability of super-small particles to penetrate the body and to interact with cells, much research is still necessary in order to determine with some certainty what is and what is not acceptable.

Another major area in need of work is constructive and rational dialogue on risk – a dialogue often colored by two opposing viewpoints: "the world is coming apart" versus "nothing is wrong." While risk should be reduced when possible, it is important to recognize not all risk can be eliminated, given societal needs. The challenge therefore is how to conduct this dialogue in a manner that is practical, accounting for the needs of a society. It is imperative to understand shutting down process facilities can have geo-political ramifications. Moving risk out of one area of the world to another accomplishes nothing more than potentially creating a weaker society with a less resilient infrastructure and supply chain. Such aspects are examined in the work of the International Risk Governance Council, which issued a white paper detailing this area (Renn et al., 2006).

As a result of the higher performance and lower energy-consumption requirements mentioned in the previous chapter, process industry installations have throughout the years become more sophisticated. Therefore, it stands to reason that recent developments in research about complex engineered system failure merit attention.

During the last decade, failures in extremely costly technology projects such as aerospace and defense initiated a more systemic approach to prevent incidents. Following Rasmussen and Svedung (2000) and starting as early as 2004, Leveson from the Massachusetts Institute of Technology emphasized in various publications the necessity of considering the functioning of an entire complex system – as opposed to only the functioning of its parts – in order to prevent its failure. As shown in Figure 4, the system is not restricted only to the technology (i.e., the production machinery/plant), but it also includes the operational staff, management and regulatory organization controlling it – both in the design and operational states, with maintenance bridging the two states.

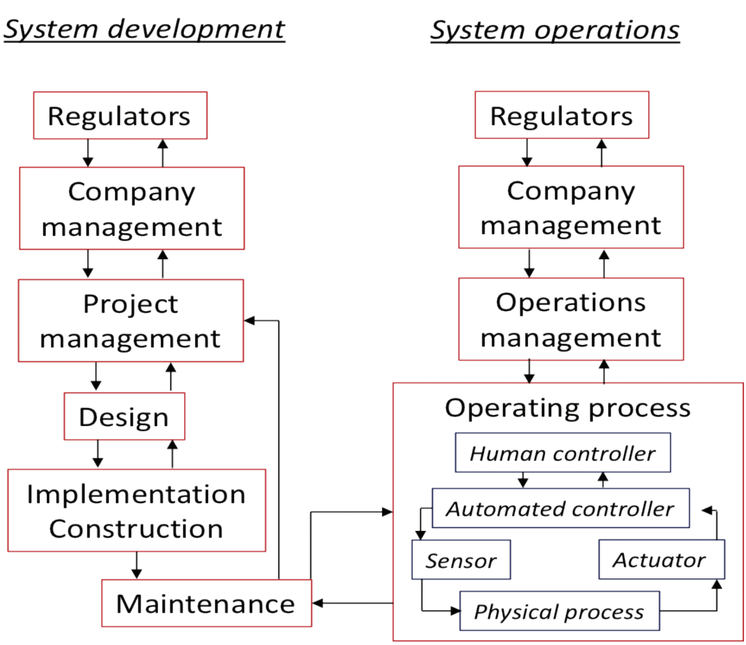

Figure 4: System development and system operations

Considering safety as an emergent system property and therefore safety measures as system constraints on the behavior of system components, Leveson (2004, 2011a and b) developed new concepts such as the System-Theoretic Accident Model and Processes (STAMP) and the System-Theoretic Process Analysis (STPA). Components can be safe, but interaction between them need not be. Also, a high reliability of components does not guarantee strong safety; highly reliable systems can be unsafe. These concepts require further elaboration in order to become practical tools.

Focused more on the process industry, Venkatasubramanian advocated a systemic approach. In a recent article (Venkatasubramanian, 2011) he makes an impassionate plea to apply system thinking to prevent accidents of the type occurring at the Deepwater Horizon platform. Some noteworthy remarks from his paper are cited below:

> *"Complexity science: One central lesson that has come through from systemic failures is the need for a prognostic approach with which one can anticipate problems, rather than relying on the current 'react-and-fix' methodology for managing systemic risks. In other words, one needs real-time intelligent decision support systems that can effectively monitor various aspects of process operations, and detect, diagnose and advise operators and engineers about incipient abnormal events. Such systems can be invaluable also in the design stage where they can be used in identifying potential hazards in the proposed design. However, in order to get there one needs to address first the crucial conceptual challenge of being able to predict how changes or dysfunctional interactions in a complex engineered system or its environment would propagate through the entire system — i.e., how does one systematically identify all potential hazards in a complex system and its environment under various conditions (Venkatasubramanian et al., 2000)? To answer this question, one needs fundamental conceptual advances in modeling and predicting emergent behavior in complex engineered systems — i.e., how does one go from the behavior of the parts to an effective description of the whole system behavior."*

> *"Multiperspective modeling: Another area where progress is needed is multi-perspective modeling. This is different from multiscale modeling where the objective is to model a phenomenon at different length (or time) scales, at different levels of detail, in an integrated manner (de Pablo, 2005). In contrast, in multiperspective models (MPM), one develops different views of an entity from the perspectives of structure,*

behavior and function (SBF). For example, for a reactor embedded in a flow sheet, MPM would comprise of structural/connectivity information, models that predict the behavior of this reactor under various conditions, both normal and abnormal, and its final impact on the intended function (Srinivasan and Venkatasubramanian, 1998). Further research is needed to pursue this line of exploration using SBF modeling, ontologies, formal reasoning methods, and so on (Lind, 1994; Venkatasubramanian et al., 2006; Morbach et al., 2007)."

"Hybrid intelligent systems for real-time decision support: Finally, the need for a conceptual framework in using the multiperspective models of a system's components along with the insights gained from complexity science to develop intelligent systems that can assist humans with prognostic and diagnostic decision support in real-time is quite clear. As noted earlier, they can also be used for critiquing design choices and conducting thorough process hazards analysis. They can be used for developing intelligent dynamic simulators for operator training. Given the real-world constraints these systems will be hybrid in nature, mixing and matching first principles-based models with data-driven empirical methods. The hybridization will also occur due to the mix of continuous and discrete event modeling methodologies."

As regards advances in the theory of causality (Pearl, 2009) and Bayesian Belief Net, modeling could lead to the dynamic risk assessment and "safety dashboard" enabling timely and correct decisions.

Implications of the presented approach for research and education are summarized in the topic points together with information in the next chapter, "Prioritization of the Research Agenda."

Prioritization of the Research Agenda

In developing this policy document, this panel was tasked with preparing a list of subject areas or topics related to process safety research and development; indexing those areas according to the relevance of topics; and estimating a time frame during which significant progress is feasible. Towards this goal, the panel recognizes that research regarding process safety should focus on industrial activities. However, due to the influence of academic activities on the formation of new generations of process safety professionals, consideration also should be given to research on teaching process safety at different engineering departments across the world.

In order to develop a research agenda for process safety, the panel decided to:

1. Focus on research needs driven by industrial incidents with special emphasis on emerging technologies
2. Identify and be aware of the global challenges facing process safety
3. Develop criteria for prioritization of the different subject areas

The following criteria are identified for prioritization:

a. loss prevention potential
b. historical losses
c. knowledge gap
d. cross-cutting benefits, multiple application
e. potential for international collaboration
f. capacity building potential
g. input/ output ratio: investment incentives help the process safety business case
h. time-scale and cost constraints

Based on these criteria for prioritization, the following top five choices have been identified:

1. hazardous phenomena: gas explosion, dust explosion and reactive chemistry
2. inherently safer design.
3. risk management, including consequence analysis
4. failure of complex systems
5. safety device and technology improvement

In line with this list of priorities, the following topics can be distinguished based on their importance, size of effort or relative newness:

1. hazardous phenomena
2. inherently safer design
3. risk management
4. consequence analysis
5. critical infrastructure protection
6. complex systems
7. resilience engineering
8. integration of process safety with occupational safety
9. organizational/ human factors: distinguish between technology and people
10. safety culture
11. mechanism to import process safety into emerging technologies
12. safety technologies, layers of protection and mitigation systems
13. life cycle/maintenance
14. process safety management knowledge: transfer, improved access; dissemination
15. standardization of process safety methods
16. integration of databases for improvement of process safety
17. easy-to-implement process safety methods for industry
18. application of process safety to drilling operations
19. natural hazard triggering technological disasters (NaTech)

Each of these topics is briefly described below:

1. **Hazardous phenomena**
Because of the emphasis on effects and damage consequences in safety consideration (generally and specifically in risk analysis), the description of hazardous phenomena resulting from the properties of released substances – directly or after mixing with air – should remain a high priority.

This holds true, in particular, where hazardous substances are present on a large scale such as in large processing complexes, transportation units, fuel and other hazardous material depots and warehouses – especially those containing volatile liquid flammables under pressure or cryogenics (LNG, LH2, LPG); stored toxics or asphyxiants (NH3, CO2); or plants in which large amounts of combustible dust is produced. Gas and dust explosions have much in common. Although systematic research has been conducted for more than 50 years, further study of gas, vapor cloud, aerosol and dust explosions is necessary, e.g., at elevated conditions of temperature and pressure as in chemical processes; when stratified clouds are of concern; for hybrid mixtures (gas and dust); or when oxidant is not simply air but oxygen, as in the case of oxy-flames. Flame acceleration processes with blast pressure generation and transition of deflagration into detonation are still not sufficiently predictable.

Better knowledge will serve not only preventive efforts but also the design of adequate protective measures. Combustion reaction kinetics and advanced fluid dynamics simulation are important as input and tools. Aerosol explosions can be violent and should be investigated separately. Continuing attention is required due to numerous incidents with considerable damage by dust explosions in smaller plants that do not belong to the chemical industry branch, such as metal, wood, plastic or textile and foodstuff processing plants. Fundamental in maintaining awareness of dust explosion safety is uncovering and preserving knowledge about the phenomenon as well as emphasizing the need for good "housekeeping" and the importance of preventive and protective measures such as compartmentation and venting.

Reactive chemical research, also a classical topic being the major cause of reactor runaway and auto-ignition, involves the measurement of thermal stability and (exothermal) decomposition rate data for important industrial chemicals and comparisons with theoretical models. Computational models, both quantum-mechanic/molecular structure and classical, are used to estimate property values and to predict chemical reactivity and compare with calorimetric measurements. For kinetic studies, activation energies can be estimated using free energy correlations, which help to extend available experimental data to predict potential reactivity hazards. Many experimental methods to analyze thermal decomposition exist. It remains, however, a challenge to predict induction periods given temperature, quantity and heat loss conditions. Autocatalysis by gaseous products, effects of contamination, pressure and access to oxygen or moisture increase the complexity of the problem. A key drawback of using conventional macroscale technology is the relatively large thermal inertia due to the calorimetric cell itself, although smart compensation methods have been developed. Miniaturized nano-calorimeters will offer enhanced sensing capabilities for testing of forensics and trace explosives. Specific attention should be devoted to anticipate the potential formation of extremely hazardous decomposition products during runaway or industrial fires to prevent Seveso-like scenarios.

Also, other property-characterizing test methods for determining sensitivity to various stimuli to initiation; influence of pressure on deflagration rate; and ability/propensity to detonate liquids and solids under various degree of confinement should be more fundamentally based and provided with modern diagnostics. Concurrently, computational tools such as Quantitative Structure-Activity Relationships (QSAR) should be further developed to enable easier estimates of properties of mixtures of substances. This holds not only for toxic properties but also for flammability and physical properties.

2. **Inherently Safer Design (ISD)**
Unfortunately, absolute inherent safety does not exist, so inherently safer solutions must be sought. This holds true for processing operations and also storage and transport of hazardous materials. There is need for further research to more quantitatively identify contributing factors (including factors such as controllability and stability). It is therefore necessary to have a measure of "inherently safer" available, for which various proposals have been made. For an overview of metrics see Khan and Amyotte (2004) as well as Kletz and Amyotte (2010). The potential contribution to ISD of recently developed process intensification technologies should be investigated. Cost factors also appear to influence implementation while management often has to be first convinced of the practical feasibility. Further work in this area is needed to extend the concepts to address the issue of security or intentional acts. There is a trend to prescribe its application within bounds by law. Finally, there is a need to conduct research on inherent safety along the lines of practical risk reduction because of the misuse and overuse of the concept of inherent safety.

3. **Risk management**
Risk is defined in ISO 31000 as the effect of uncertainty on objectives, whether positive or negative. It is the quantifiable negative element of safety that is otherwise immeasurable. Risk management is the identification, assessment and prioritization of risks followed by coordinated and economical application of resources to minimize, monitor and control the probability or impact of unfortunate events or to maximize the realization of opportunities. Risks can result from process failures (at any phase in design, development, production and sustainment life-cycles as well as storage and transportation), incidents, natural causes and disasters as well as deliberate attack from an adversary, or events of uncertain or unpredictable root-cause. Risk management requires one to: i) identify, characterize and assess hazards/threats, hence generation of scenarios; ii)

assess the vulnerability of critical assets through damage models and probit functions; iii) determine the risk, i.e., the expected consequences and likelihood of an event and corresponding confidence limits; iv) identify ways to reduce those risks; and v) prioritize risk-reduction measures based on a given strategy and optimize plant layout.

Risk management thus builds on the results of risk analysis, assessment and installed risk-reduction measures. To that end, existing tools must be improved in order to cope with the relatively large uncertainty that leads to loss of confidence in results. It also is desirable to be able to perform dynamic operational risk analysis accounting for effect of aging/wear on failure rates; duration of testing intervals; fluctuations in exposure of people, e.g., by presence of temporary workers; and fluctuations due to varying type of operation: normal or abnormal in start-up or shut-down. Ideally this could lead, together with inputs of various process sensor signals, to a risk "dashboard" that will alarm when a certain level of risk has been exceeded.

The effort required to conduct an analysis should be reduced. This can be achieved by making better use of incident histories to generate scenarios that take into account cascading and escalating events (domino effects). Predictive incident modeling as a research topic can serve to validate scenarios. Also badly needed are publicly available failure data to estimate failure frequency values given the conditions in which components operate, their treatment, maintenance, duration of operation and mode of failure. The use of advanced statistical means, introduction of new methods such as Bayesian approaches to data processing (Christensen et al., 2011) and Bayesian Belief Net (BBN) to model causal chains (Darwiche, 2009) will help further improve the consequence models (see no. 4 below). The BBN may be expected to replace fault and event trees including bowties, accounting for full distributions, and hence, to propagate uncertainty, to remain transparent and to enable inference. The nets are an efficient tool to support decision-making through applying cost-benefit analysis and the concept of utility. Despite uncertainty, a decision will be made more rational by the information generated with an analysis and delineation of at least the known uncertainty.

Research is required on risk acceptance criteria since in many situations, (e.g., licensing) conflicting interests exist where a clear borderline of tolerability should be available, but due to large uncertainty margins, an area of fuzziness may exist. This uncertainty may lead to conflicting interests regarding risk tolerance, overall risk, societal benefit and the balance between all of these factors. Such aspects are examined in the work of the International Risk Governance Council, which issued a white paper detailing this area (Renn et al., 2006).

4. **Consequence analysis**

In many cases of public outcry regarding planned or existing plants or transportation routes, in the pro versus con debate, focus shifts to the low expected frequency – high consequence effects. Disastrous consequences can be imagined easier than the so-called "once-in-a-million-years" event frequencies. As mentioned, both consequences and failures are topics of large uncertainty, but for the former it is often possible to realistically collect information because of the use of theoretical models, experimentation and simulation by computation. For failure data, history is often the only source. The validity of such simulation results relies on the range of experimental data and appropriateness of the model, impacting the ability to extrapolate. Consequence analysis starts with defining the source term and the subsequent phenomena of evaporation after release, dispersion, various types of fires, gas, vapor cloud, aerosol and dust explosions – in all of which turbulence effects play a major role. Variability in Boiling Liquid Expanding Vapor Explosions (BLEVE) is still a topic of further research with respect to both the time to burst and the violence of the event. The same holds true for various types of explosions of condensed substances, e.g., in a fire. In addition to methods that produce more accurate effect predictions, better models are needed for the vulnerability of structures and the environment for the damaging effects and for residual effect after functioning of protective devices such as reliefs and water sprays. This depends significantly on the progress achieved in means of computation such as (reactive) fluid dynamics, finite element approach and material property knowledge. There are large uncertainties regarding the probit relations for the probability of fatality, while injury models for emergency planning are badly needed but almost non-existent except for fire. Case histories mostly do not contain sufficient details to make information useful, and research on improved formats for event information could help. Accurate information on large-scale incidents (development, effects and consequences) is essential for checking models, and publication of exhaustive and complete case histories should be stimulated.

Another class of hazards is the toxicity of substances. In particular, in case of accidental releases the acute toxicity is relevant. Many exposure data are old and not very reliable while confidence limits are unknown, especially with respect to differences in individual responses. However, there is an improved possibility to determine toxicity via physiologically-based pharmacokinetic modeling and non-animal testing. For emergency response and risk analysis in general, beside the estimation of fatality in a given situation, there is a great need for injury prediction.

5. **Critical infrastructure protection (CIP)**
CIP is a concept that relates to the preparedness and response to serious incidents that involve the critical infrastructure of a region or nation. It should be realized making use of nos. 1-4 in this section.

The U.S. American Presidential directive PDD-63 of May 1998 set up a national program for "Critical Infrastructure Protection." This effort recognized certain parts of the national infrastructure as critical to the national and economic security of the United States and the well being of its citizenry and required steps to be taken to protect it. As updated on December 17, 2003 through Homeland Security Presidential Directive HSPD-7 for Critical Infrastructure Identification, Prioritization and Protection, the directive defines the infrastructure as the physical and virtual systems that are "so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety." The Chemical Facility Anti-Terrorism Standards (CFATS) applies to any facility that manufactures, uses, stores or distributes certain chemicals above a specified quantity and is administered by the U.S. Department of Homeland Security.

In Europe, the equivalent European Programme for Critical Infrastructure Protection (EPCIP) refers to the doctrine or specific programs created as a result of the European Commission's Directive 2008/14/EC, which designates European critical infrastructure that in case of fault, incident or attack could impact both the country where it is hosted and at least one other European Member State.

6. **Complex systems**
In trying to prevent disastrous mishaps due to this kind of failure, research needs to be conducted in complexity science, multi-perspective modeling and hybrid intelligent systems for real-time decision support as described in the previous chapter. In the design stage as well as during operation of a system it is required to have high-level controls on both the i) safe component functioning and ii) correct and safe interaction between

components. The approach needs practical tools both for the technical and organizational aspects. For example, research will be required to develop effective Process Safety Performance Indicators (PSPIs) monitoring the performance of the safety management system. The PSPIs can be seen to act as part of the system's sensors, transmitting signals – albeit often weak ones – assisting decision-making (processer stage) and initiating action of operator/management (actuator). Longer-term trends should be made visible by applying advanced statistical tools as well as the system dynamic modeling of which various examples are given by Leveson and coworkers (Leveson, 2011b). In that case, time constants should be (semi-) quantified, which presents an ambitious goal. Much of the above also has a bearing on resilience engineering, treated in No. 7.

7. **Resilience engineering**

Resilience is the capability of a system or process to absorb severe and unexpected disturbances. Within reasonable time and cost limits, this means recovering a system from an upset state or a state in which mishap is close to (or already beyond) the normal safe state. Resilience engineering should help counteracting the previously mentioned failure potential. During the design stage, by cost pressure, redundancies and reserves are often minimized or eliminated as much as possible. The same holds true for the organization of the workforce and management (Hollnagel et al, 2006). Therefore, it makes sense to develop a quantified resilience measure; an index that measures various properties of process and organization such as flexibility, controllability, alertness and ability to receive and react to weak alarming signals; clear procedures and administrative controls that cover abnormal situations; and effective emergency response plans. Process simulation and risk analysis will help to create scenarios that serve to test resilience but will also assist in obtaining a more effectively trained crew and management. In addition, the resilience of the organization to continue functioning with a sufficient level of reliability should be analyzed and tested (Gifun, 2010). In this way, the high reliability organization (HRO) described by Weick and Sutcliffe (2007) will turn into a high reliability, resilient organization (HRRO).

8. **Integration of process safety with occupational safety**

Process safety management of highly hazardous chemicals is the proactive identification, evaluation and mitigation or prevention of chemical releases that could occur once or semi-continually as a result of failures of process, procedures or equipment. The major objective of occupational safety for process plants is to prevent unwanted releases of hazardous chemicals, especially into locations that could expose employees, contract workers and others to serious hazards of an acute or chronic nature. In addition, occupational safety targets creating work conditions that prevent injuries in general. To achieve both, knowledge is required of the system and the lines of defense and not only of the last protective layer, the personal protective equipment and the prevention of slips, trips and falls. Traditionally, the fields of process and personnel safety developed in parallel, but generally different disciplines (engineering versus human resources/psychology) were involved to manage them. However, while the type of measures may be different, they share commonalities such as the hazards, their identification and the all-embracing safety attitude and safety culture to take the correct measures towards prevention and protection. Further integration should be pursued although, in general, regulation and compliance inspections fall under the jurisdiction of different ministries/agencies. Unification also may help to eradicate the false belief that improvement in personnel safety automatically means improvement in process safety. This misunderstanding has contributed to fatal consequences in some disastrous accidents.

9. **Organizational/Human factors**

The area of human factors represents the integration of facilities, management systems and people. It includes workplace design, equipment design, work environment, physical activities, job design, information transfer and personal factors. In further detail, the area covers:

a. Procedures/simulations to guide and prepare operators, also for abnormal situations
b. Human-machine interface ergonomics, control room ergonomics
c. Communication within teams and between shifts
d. Human reliability analysis
e. Training/competency, learning process

Analysis and optimization of the process of receiving information, decision-making and action requires further research with respect to the type of information to be received, timing, crew functioning, that which can be automated and that which can be left to the human operator/manager. This area also encompasses alarm management and effective handling of abnormal situations that are a major source of incidents. General conditions in the organization for safe work should be ascertained by the presence of a properly functioning, risk-based safety management system that is monitored by process safety performance indicators while third-party audits should verify both technical and organizational safety.

Human reliability has been extensively studied for nuclear safety as a function of reliability (e.g., Technique for Human Error Rate Prediction (THERP), Swain and Guttman, 1983); and as a function of human (team) failure to grasp and assess an abnormal situation and to act correctly (e.g., A Technique for Human Event Analysis (ATHEANA), NRC, 2000). Neither technique produces a complete picture. Given a technical step event tree, a parallel crew response tree can be constructed with procedural decision nodes and observed team deviating path branches for which probability and effect can be measured through simulation (Kelly, 2011). To minimize human error design of installations, control rooms and critical buildings should be human-centered similar to ISD with respect to minimizing risk. This holds true for the organization as a whole; in standard ISO 26000:2010 a guideline is given on social responsibility. Human reliability issues also must be taken into account in emergency operation and crisis management.

In the realm of knowledge transfer, smart learning systems, and virtual training, simulators are expected to play a significant role in process safety performance in the 21st century. The essentials of smart learning systems include an accurate model of the learner, a model of the knowledge domain and a machine-readable "learning strategy" to evaluate the differences between the two models. It takes advantage of new technology, skills and knowledge. For example, experts often find it easier to relate stories about past cases than to formulate rules. Similarly it is true in the HAZard and OPerability (HAZOP) analysis domain that rules or models are hard to construct to automate "non-routine" analysis. To overcome this problem, an important artificial intelligence technique – case-based reasoning (CBR) – is adopted to augment the reasoning machines embedded in the existing HAZOP expert systems. CBR is both a pattern for computer-aided problem solvers and a model of human cognition (Zhao et al., 2009). The central idea is that the problem solver reuses the solution from past cases to solve a new problem. This approach also offers the possibility to make better use of the information contained in incident databases.

10. **Safety culture**

The safety culture of an organization has a significant impact on its safety performance. Although the level of safety culture of a work community can be subjectively observed immediately after entering that community, an objective measure is difficult to define. Moreover, establishing effective improvement, if needed, is not an easy task, particularly when this must be accomplished within a relatively short timeframe. A successful program is "Hearts and Minds" by Shell Exploration & Production that Hudson and coworkers developed over a period of years, building on Tripod and Reason's Swiss Cheese model approach (Hudson et al., 2004; Hudson, 2007). An extensive overview of safety culture awareness, methods and development is given by Guldenmund (2010) in his dissertation. With regard to assessing the level of safety climate and improving measures, see Zohar's (2010) summary of 30 years of research in the field. More practical and generally applicable tools are needed to obtain more effective and quicker results.

11. **Mechanism to import process safety into emerging technologies**
Due to sustainability requirements, a significant shift from conventional fuels (energy carriers) to biofuels, natural gas and hydrogen for power generation and automotive uses can be expected. These changes will create new hazards by enlargement of scale and widespread distribution, particularly in the case of hydrogen. Combusting coal will entail carbon capture and storage. In the case of post-combustion separation of carbon dioxide, existing technologies rely on large scrubbers and desorption towers with gas-treating solvents and subsequent transportation of compressed carbon dioxide to the sequester cavities. The scale also will be large for newly developed technologies, e.g., pre-combustion separation or oxy-fuel process. Additionally, new materials, such as nano- and biosynthetic materials, are produced with unknown or poorly understood properties that will require intensive research for their potential hazards.

12. **Safety technologies, layers of protection, mitigation systems**
In this area, much has already been accomplished, e.g., fail-safe architectures, and inherent safety features of components are known and still developing. There has been significant improvement in the reliability performance levels of functional safety barriers or layers of protection composed of Safety Instrumented Systems (SIS) as emergency shutdown. An impressive step forward is represented by the issuing of the international standard on functional safety, IEC 61508, and its derivation for the process industry, IEC 61511 (or U.S. ANSI/ISA-84.00.01-2004), both of which are unique in that they are risk-based and specify reliability levels. This provides a certain guarantee of functioning, yet existing technology exhibits weaknesses that are revealed throughout time. Many problems find their origin in inadequate knowledge about the risks in a specific case when selecting available controls to be used in an installation. This can lead to either overdesign or insufficient coverage. Uncertainty about reliability of a layer can arise from the spread in value of probability of

failure on demand of layers; common cause failure of layers; insufficient testing and maintenance; and human factors. Effectiveness of mitigation systems – active, as in venting devices or water sprays, or passive, as in bunds – appears to behave (not seldom) differently under real emergency conditions than assumed during the development stage. Improvement of models is desirable, as is the determination of residual effects on the environment.

13. **Life cycle/maintenance**

The Safety Life Cycle (SLC) is the series of phases from initiation and specifications of safety requirements, covering design and development of safety features in a safety-critical system and ending in decommissioning of that system. This is particularly important in view of an aging plant. The concept of a SLC has been incorporated into many national and international standards. One such example is the standard mentioned under topic No. 12, IEC 61511 (U.S. ANSI/ISA-84.00.01-2004). The preceding ANSI/ISA S84.01-1996 standard was the first-published functional safety standard and was recognized by the U.S. Occupational Safety and Health Administration as an example of Recognized And Generally Accepted Good Engineering Practice (RAGAGEP). The Safety Life Cycle, per IEC61508 – or 61511 for process industry –similar to ISA, can be categorized into three broad areas:

i) The analysis phase focuses on the identification of hazards and hazardous events; the likelihood of these hazardous events and their potential consequences; the availability of a layer of protection as well as the need for any Safety Instrumented System (SIS); and the allocated Safety Integrity Level (SIL).

ii) The realization phase focuses on design and fabrication of the SIS. The SIS is used as a layer of protection between the hazards of the process and the public, i.e., the worse the potential hazard, the more layers required for prevention/protection.

iii) The operation phase accounts for start up, operation, maintenance and eventual decommissioning of the SIS.

Although a probabilistic approach through reliability engineering provides methods to optimize maintenance, there is still a need for further improvement. Risk-based inspection forms part of that need. In contrast, maintenance effects should be better accounted for in risk assessment.

14. **Process safety management knowledge transfer; improved access; dissemination**
Knowledge transfer, previously detailed in topic no. 9, is the set of practices that has been learned through experience and that gives a company a more competitive edge (Zhao, 2012). In the process safety arena this set of practices amassed from experience is critical since the room for error is much smaller. Modern and diverse knowledge transfer techniques are needed, quite simply, because corporations do not have memories. Most knowledge resides with the employees, and once they leave a corporation, that knowledge leaves with them. This continues to be the bane of process safety, as errors get perpetuated and incidents repeat. A system can be created to keep a corporate memory by accumulating knowledge as it is developed and saving it in an organized manner, to be easily found and used by others as needed. Accurate, complete and updated knowledge is the basis for a safer plant. Organizations without appropriate knowledge transfer procedures and technologies do not have organizational memory. Knowledge transfer needs to be diverse and meet the needs of the organization. Knowledge transfer techniques include: updated design documentation and basis; classroom training; computer-based training; case study-based training programs; incident databases; smart learning systems; expert advisory and decision-making systems; and virtual training simulators.

There is a strong need for research on the pedagogy of process safety and the integration of knowledge for both undergraduate engineering students and workers in industry. Problem-based learning is important in this regard. Various process safety knowledge tools are available (e.g., Center for Chemical Process Safety (CCPS), Safety and Chemical Engineering Education (SACHE) and Institution of Chemical Engineers).

Greater efforts should be made to advance the awareness and implementation of process safety in small- and medium-sized enterprises. In this respect, the importance of certifications related to incorporation of personnel qualified in process safety is important. This fact implies the inclusion of governmental institutes in developing countries to improve the communication of available information to entities with lack of resources.

The availability of handheld, computer-based decision support systems at affordable prices is providing an ever-increasing capability for emergency responders and operators to obtain a wealth of information on many elements needed to respond to a wide variety of emergencies, especially those that may be related to complex HAZMAT situations. The degree of preparedness will increase based on realistic local scenarios and risk assessment, including availability of resources and quality of training. Responders should have a thorough and independent evaluation of available systems.

Finally, virtual simulators are needed to help improve knowledge transfer. Virtual simulators lead to increased safety without any additional risk to trainees, instructors, site personnel or property. Virtual training also leads to enhanced information retention and productivity upon beginning work.

15. **Standardization of process safety methods**
The international standardization of methods has a number of advantages, provided it does not impede progress by "freezing" the state of affairs. These advantages are: i) the safety tools and systems available to small- and medium-sized companies can be increased to the level of the major multinationals; ii) the terminology and definitions become more uniform, which improves communication in the branch and supports better education; iii) fostering the integration of risk assessment results into business decisions and governance; iv) prevention of false competition since the safety requirement effort to be made is equal to all in proportion to the size and risk of the operation. The international standard IEC/ISO 31010 risk management – risk assessment techniques, edition 1.0, 2009/11 is a good example. Further work in this direction is encouraged.

16. **Integration of databases for improvement of process safety**
Process safety databases are used to enable scenario generation and risk identification; reduce risk; and prevent loss. In the chemical industry, the utilization of process safety databases is in an embryonic stage. Many organizations in several countries collect data on process incidents. These organizations differ from each other in their interests, data collection procedures, definitions and scope. However, major benefits are possible by employing incident databases. Extensive efforts are required to integrate information from the data sources as well as to identify the effects of the individual aspects of data collection procedures on the quality and completeness of the data. The form of some databases must be altered for certain database applications, especially for development of risk-reduction models and process improvements. Goodwill and an open-minded approach are required from generic database stakeholders to establish the effective improvement methodology that is described here. Two general approaches are suggested:

i) Interoperable databases (also known as federated or distributed systems). These databases consist of a series of data sources that communicate among themselves through a multi-database query. This requires a new interface through which a data source, such as an existing database, can be viewed and manipulated. In this environment, data reside in computers or database servers located in a variety of places, but each is linked through a computer network and viewed via the master interface. With interoperable databases, one computer can access or add to another computer's information.

ii) Fused databases. Data fusion (also known as data warehousing) combines information from multiple sources for the one-time use of making them accessible for data integration. The sources of fused data can be eliminated when the data is migrated to a central location. They also can continue to exist independently to serve various business processes. Ultimately, all fused data reside in a single database server with substantial processing and data storage capacity. When fusing data, the variety of databases or formats as well as sources and applications can make it difficult to ensure the integrity of the information in each database. This complicates the task of mapping the movement of data from old systems to a new system.

17. **Easy-to-implement process safety methods for industry**

Due to the sophistication needed to make progress, the gap in the level of theoretical knowledge between academia and most industry experts tends to widen and becomes an obstacle to communication. This can cause a decrease both in the flow of industry experience to academia and the implementation of newly acquired knowledge to industry. Special effort should be made to counter this trend. Easy-to-implement methods require the developer to fully master the method and the knowledge it is based on in order to describe complex phenomena in simple terms and make the method transparent and user friendly. This task will benefit from results in topics nos. 14 and 15.

18. **Application of process safety to drilling operations**

With the backdrop of the Macondo gulf coast disaster and other high-profile offshore issues (see the final Macondo report of the Deepwater Horizon Study Group, 2011, initiated and led by Bea of UC Berkeley), there is an immediate need for the development of theories, analytical techniques and technology to improve offshore infrastructures from all sources of failure including design, operations, management, natural disasters and intentional acts such as terrorism. Based on the body of knowledge already collected in the North Sea after the Piper Alpha disaster, this research should focus on developing theories and techniques that apply to various types of process safety issues faced by the refinery industries that include such issues as structural integrity, layers of protection, off-gas handling, risk assessment and consequence analysis, human error and safety culture. Test beds may include processing facilities and complex structures within the offshore infrastructure, transportation vehicles (e.g., ship and helicopter) and the marine environment. This research is aimed at better integrating the concepts of process safety into the design and operation of offshore platforms and using this knowledge to improve their safety performance such that the unit/process is not vulnerable to certain failures. For example, the last line of defense against a blowout is the blowout preventer (BOP). However, the BOP has proved not to be a highly reliable safety function. It could thus be argued that the operation is vulnerable to single-point failure.

19. **Natural hazard triggering technological disasters (NaTech)**
There is growing evidence that natural disasters can trigger technological disasters and that these joint events may pose tremendous risks to regions that are unprepared for such events. The multiple hazardous material releases triggered by the Turkey earthquake of August 1999 and the Japanese earthquake disaster of 2011, which besides the Fukushima Daiichi nuclear disaster also caused multiple LPG BLEVEs (liquefied petroleum gas-boiling liquid expanding vapor explosion) at refinery sites, are examples of the potential danger of a NaTech disaster occurring near populated areas. While safety techniques have been developed and implemented to prevent or contain incidents at industrial facilities and other hazardous installations, they are typically not designed to accommodate releases that are triggered by, and are simultaneous with, natural disasters. The U.S. Occupational Health and Safety Administration requires that the process safety management (PSM) analysis identify and mitigate hazards involved in processes that use hazardous materials. Hazards considered in the analyses are those that would occur under “normal” operating conditions, not those that might be generated by external hazards such as earthquakes or flooding. The European Commission has published a set of guidelines to help member states fulfill the requirements of the Seveso II Directive. The guidelines specifically recommend analyzing the potential effects of natural hazards (e.g., floods, earthquakes, extreme temperature changes and winds) and other external hazards in the hazard analysis. These guidelines, however, do not provide specific actions or methodologies that can be taken to prevent, mitigate or respond to NaTech events.

The systematic study of the interaction between natural and technological disasters is an area that has attracted increased attention. Cascading events are more likely to occur during a natural disaster than during normal plant operations because a natural disaster, particularly earthquakes, increases the likelihood of multiple, simultaneous failures. Moreover, common cause failures (e.g., power supply disruption) may cause the unavailability of mitigation systems such as water curtains or catch basins. The unavailability of critical infrastructures (e.g., bridges and roads) also may result in external rescue teams rendered unable to reach a site. If not taken into account during the planning process, emergency response needs are likely to overwhelm response capacity. However, there is little information available on the actual risk of NaTech or on what actions are being taken by local governments and communities to prevent and prepare for these types of events.

The panel has restructured the above list of topics and classified the different items across two categories: technical and organizational topics. Table 1 illustrates this.

Topic No.	Technical Safety Topics	Topic No.	Organizational Safety Topics
1, 11	Hazardous phenomena, properties of substances	8	Process + occupational safety
2	Inherently safer design	9, 10	Human factors, safety management, safety culture
12, 13, 18	Safety technologies, protection layers, drilling	14, 15, 17	Knowledge transfer, learning, standards, easy methods
3, 4, 5, 16, 19	Risk assessment, consequence analysis, NaTech	3	Risk management, decision-making
6, 7	Complex systems, resilience	6, 7	Complex systems, resilience

Table 1: Categorization of research topics according to their main character

Table 2 lists these topics with their integrating concepts and implementation mechanism. Integrating concepts imply the underlying mechanisms for the topics listed while the implementation step refers to the enabling tools needed to address the particular topic.

The panel recommends further consideration be given to the:

a. selection process for top few/five to initially pursue
b. identification of specific projects in each area
c. funding opportunities
d. suggestion of other potential research areas (e.g., open calls in process safety journals)

Table 2: Topics with their respective integrating concepts and implementation mechanism

Research Topics	Integrating Concepts	Implementation
1. Hazardous phenomena	Substance property	Test standardization
2. Inherent safety design	Metrics	Business; regulation
3. Risk management	Analysis; cost/benefit	Business; regulation
4. Consequence analysis	Computation	
5. Critical infrastructure protection	Security	Regulation
6. Complex systems	Systems analysis	Risk reduction
7. Resilience engineering	Metrics	Risk reduction
8. Integration of process safety with occupational safety	Safety principles	Communication
9. Organizational/ human factors	Human-centered design	Communication, analysis
10. Safety culture	Management attitude	Communication
11. Mechanism to import process safety into emerging technologies	Hazard identification	Regulation
12. Safety technologies, layers of protection, mitigation systems	Safety principles	Business; regulation
13. Life cycle/maintenance	Safety principles	Business; regulation
14. Process safety management knowledge: transfer, improved access; dissemination	Course materials	Education
15. Standardization of process safety methods	Sharing best practices	Business; regulation
16. Integration of databases for improvement of process safety	Political will	Super database
17. Easy-to-implement process safety methods for industry	Feel for industry problems	Guidelines business; regulation
18. Application of process safety to drilling operations	Process safety thinking	Business; regulation
19. Natural hazard triggering technological disasters (NaTech)	Risk analysis	Regulation

Challenges with academic funding

Funding agencies of research generally prefer direct and spectacular "breakthrough" work, leading to new materials or technology that promises industrial application, large economic benefit or better sustainability – not safety related research that will "only" prevent losses. There also is a systematic negative perception regarding process safety research and development in academic circles; the management of the academic community does not appreciate the importance of process safety. For example, out of approximately 150 chemical engineering departments in the United States, only a handful teaches chemical process safety. In general, safety training focuses on personnel and occupational safety rather than on process safety. Chemical process safety should be imbedded in all courses for chemical engineers.

The program criterion of the American Accreditation Board for Engineering and Technology (ABET) that defines chemical engineering curriculum does not even mention process safety, hazards or risk analysis while such words are included for construction, mining and petroleum engineering programs. ABET's general criteria include health and safety in Criterion 3, defining program outcomes. However, this is a common requirement affecting all engineering programs. Fortunately, ABET in its new guidance started requiring the analysis and control of process hazards to be included in the program-specific criteria for chemical engineering. This is expected to impact chemical engineering departments throughout the United States from 2012 onwards.

Therefore, it is prudent to generate a large international program that can provide the critical mass and visibility required to ensure an adequate treatment of process safety engineering. The problems encountered by process safety practitioners exist worldwide. It is recognized that an incident occurring in one part of the world has the potential to affect other parts of the world in a number of aspects. Catastrophes like Bhopal, Chernobyl or Fukushima Daiichi not only impact the atmospheric environment for a large radius, but they also have crippling effects for the global economy. Despite the fact that exactly the same process safety problems do not occur in all countries, there is some consistency and a clear global interconnection among them.

A legitimate business case can be made regarding the costs to repair the damage of a preventable, major incident versus the investment in better education and research. The gains of prevention easily will outweigh the costs of funding the global university effort for one year. Immediately after an incident, public support for a preparedness effort is observed, but that support soon wanes and is replaced with a general complacency as more time passes. Only few programs have longer-term effect, such as those established in Norway where the government awards exploration/production licenses for the oil and gas fields under the condition that companies deposit a certain percentage of their revenues into a research fund.

Clear and global need for academic research

The manufacturing industries clearly demonstrate the need for global industrial best practices regarding process safety. Companies that operate in several countries find it difficult to follow and implement different safety standards for similar processes or unit operations. Additionally, there is an uneven supply and demand for process safety professionals. Many companies report shortages in hiring highly qualified process safety professionals in developing countries. Moreover, in many cases the level of process safety implemented at a given facility is not determined only through the decisions taken at the headquarters of multinational companies but also by the quality and commitment of the personnel operating at the local level. Therefore, it is necessary to address the impact of the different local cultures on the process safety practices. In addition, the continuing increase of industrial complexes near cities and harbors with the corresponding increase of stored hazardous materials causes higher risk, which requires protective measures.

Unfortunately, safety problems are to a certain extent similar to terrorism problems; process safety engineering becomes relevant to the public only when the media reports disasters. As a trend, the governments from less-developed countries implement process safety training only when foreign funds are available. Local priorities are different, and many times process safety research and development projects are dominated by the agendas of some international agencies. Once a given project is no longer funded through international channels, the local governments lose interest in it. This is not a sustainable approach. Many of these countries are capital-poor but rich in problems that would significantly benefit from the insights of process safety professionals. This is compounded by a shortage of such professionals with the desired diversity and depth of expertise needed (Sagnier and Le Floch, 2012).

Independent academic global organization

There are many organizations involved in process safety research and development, but none of them are acting as a global permanent structure. The establishment of an academic, independent organization dedicated to coordinating process safety research projects on a global basis is recommended.

The fundamental objectives of the organization should be:

- Globalization: The organization should serve as the global knowledge base for process safety research and development. It should identify and develop global research challenges, influence local activities and play an active role in the genesis of different rules and regulations affecting process safety. All stakeholders should perceive the organization as an objective global authority regarding process safety.

- Support: The organization should serve in a support role for general education and research activities focusing on process safety. The organization should become involved in the accreditation of different engineering departments and assist universities in developing standardized curricula. It is essential to incorporate process safety in basic engineering courses rather than focus on separate courses. The organization should capitalize on global best practices for process safety.

- Resolution: The organization should actively be involved in solving the disconnect among the customers and funders of process safety research and development projects. In many cases the customers (who include those from industry and the public) are not adequately represented to government funding agencies.

- Awareness: The organization should focus on promoting and enhancing the reputation of process safety.

- Value: The organization should demonstrate the added value of technical knowledge at a global level. The experience with HAZOP could serve as an example.

- Fundraising: The organization should focus on optimizing expenditures by integrating efforts, raising funds, developing synergies and preventing overlaps. For example, there is a disconnection between the academic community (that lacks funding) and industry (where there is a large effort regarding process safety).

• Dissemination: The organization should actively be involved in global events regarding the promotion and development of trans-industry crosslinking activities for all stakeholders. The organization should focus on journal-related activities in order to provide a broad dissemination of its knowledge base. Safety is related to lives and sustainability, and process safety should become part of the global corporate responsibility.

The organization should support and provide funding for the development of its fundamental objectives rather than for specific projects. The main sources of funding are expected to be:

• Global transnational companies: Process safety research and development is under-funded. The business community should be incorporated into this effort.

• International organizations: Large international organizations such as the United Nations Organizations or the Organization for Economic Cooperation and Development fund different projects related to process safety research and development. Other professional organizations also may be interested in supporting such projects.

• Governments: The organization should interact with different governments in order to coordinate multi-lateral funding exercises rather than support local fundraising for specific projects. On the level of the EU there is the European Technology Platform on Industrial Safety (ETPIS) that recognizes the importance of human and organizational factors with respect to safety management systems and safety culture, which will be instrumental in coordination activities and action towards the EU Commission.

In principle, any individual or entity that helps fulfill the fundamental objectives of the organization should be accepted as a member.

In addition to general membership, among the potentially different stakeholders, it is necessary to identify the following:

• Executive members: These members work on a full-time or part-time basis to develop the fundamental objectives of the organization.

• Supporting members: These members are expected to generate resources for executive membership. Multinational companies, international organizations and different governments should be invited to join the organization as supporting members in order to fund its activities.

• Research members: These groups identify relevant research topics for review by the supporting and executive members.

As an immediate action, the panel has appointed Dr. Sam Mannan, director of the Mary Kay O'Connor Process Safety Center of the Texas A&M University System, to establish a committee to develop the charter of the organization. This committee is to:

1. Identify other related organizations and stakeholders.
2. Identify the initial supporting members and define baseline. contributions.
3. Work with these initial supporting members to develop a proposed research program and budget.
4. Organize a second workshop to review the charter and approve and constitute the organization within a year. Further meetings should rotate among different countries.
5. Request from general journals (e.g., Harvard Business Review, Safety Science, and American Institute of Chemical Engineering Journal) a special publication/ issue to promote this activity.

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Acronyms

AIChE	American Institute of Chemical Engineers
AIST	Japanese National Institute of Advanced Industrial Science and Technology
BBN	Bayesian Belief Network
BCP/BCM	Business Continuity Planning/ Business Continuity Management
BOG	Boil-off gas
BOP	Blowout Preventer
CATS	Chemical Accident Tracking System
CBR	Case Based Reasoning
CCPS	Center for Chemical Process Safety
CCS	Carbon Capture and Storage
CEN	Comité Européen de Normalisation (French: European Committee for Standardization)
CENELEC	Comité Européen de Normalisation Électrotechnique (French: European Committee for Electrotechnical Standardization)
CFD	Computational Fluid Dynamics
CNG	Compressed Natural Gas
CSB	Chemical Safety Board
CSP	Concentrating Solar Power
DDT	Deflagration-to-Detonation Transition
DME	Dimethyl Ether
DNS	Direct Numerical Simulation
DNV	Det Norske Veritas
DPA	Delta Process Academy
DSC	Differential Scanning Calorimetry
ENISA	European Network and Information Security Agency
EPA	U.S. Environmental Protection Agency
ERA-NET	European Research Area Network
ESENER	European Survey of Enterprises on New and Emerging Risks
ETA	Event Tree Analysis
ETPIS	European Technology Platform on Industrial Safety
EU	European Union
EU-OSHA	European Agency for Safety and Health at Work
EU-VRi	European Virtual Institute for Integrated Risk Management
FEV	Full Electric Vehicle

FMEA	Failure Mode and Effect Analysis
FPSO	Floating Production, Storage and Offloading
FSD	Flame Surface Density
FTA	Fault Tree Analysis
HAZMAT	Hazardous Materials
HAZOP	Hazard and Operability Analysis
HF	Human Factor
HLG	High Level Group
HRRO	Highly Reliable, Resilient Organization
HTF	Heat Transfer Fluid
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
INERIS	Institut National de l'Environnement Industriel et des Risques (French: National Institute for Environmental Technology and Hazards)
iNTeg-Risk	Early Recognition, Monitoring and Integrated Management of Emerging, New Technology related Risks
IRAS	Incident Reporting and Analysis System
IRGC	International Risk Governance Council
ISHPMIE	International Symposia on Hazards, Prevention, and Mitigation of Industrial Explosions
ISO	International Standard Organization
JLPPI	Journal of Loss Prevention in the Process Industries
JST	Japanese Science and Technology Agency
KPI	Key Performance Indicator
LES	Large Eddies Simulation
LNG	Liquefied Natural Gas
LOC	Lab-On-a-Chip
LOPA	Layers of Protection Analysis
LPG	Liquefied Petroleum Gas
MARS	Major Accident Reporting System
METI	Ministry of Economy, Trade and Industry of Japan
MKOPSC	Mary Kay O'Connor Process Safety Center
NGO	Non-Governmental Organization
OECD	Organization for Economic Cooperation and Development
OSHA	U.S. Occupational Safety and Health Agency
PESI	Spanish Platform on Industrial Safety
PFD	Process Flow Diagram
PHA	Process Hazards Analysis

PIF	Performance Influencing Factors
P&ID	Process and Instrumentation Diagram
PIV	Particle Image Velocimetry
PLIF	Planar Laser-Induced Fluorescence
PM	Properties of Materials
PPE	Personal Protective Equipment
PPP	Public Private Partnership
PSEP	Process Safety and Environmental Protection
PSM	Process Safety Management
PSP	Process Safety Progress
PTEOO	Process Technology, Engineering, Operation and Organization
QRA	Quantitative Risk Analysis
QSAR	Quantitative Structure-Activity Relationship
QSPR	Quantitative Structure-Property Relationship
RDI	Research, Development and Innovation
RANS	Reynolds Averaged Navier Stokes
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RISCAD	Relational Information System for Chemical Accidents Database
RISS	Research Institute of Science for Safety and Sustainability
SHM	Structural Health Monitoring
SMEs	Small- and Medium-Sized Enterprises
SRA	Strategic Research Agenda
SSCT	System Safety Concepts and Tools
STAIR	Standardization, Innovation and Research
UDM	Unified Dispersion Model
UK	United Kingdom of Great Britain and Northern Ireland
U.S.	United States
UV	Ultra Violet

Through the utilization of science and engineering, researchers and practitioners can help achieve effective process safety.

Perhaps more so than any other field, process safety suffers from a widespread neglect rooted in a false sense of security. Specifically, the importance of process safety typically becomes evident and emphasized only after negative events have taken place, and losses of property and life have occurred.

The risk remains for serious and significant industrial incidents, and to make further progress towards the prevention and mitigation of such incidents, a deeper examination of their root problems is necessary.

With that in mind, the Texas A&M University System Mary Kay O'Connor Process Safety Center convened in 2011 an unprecedented gathering of academicians from around the world to develop, "Process Safety Research Agenda for the 21st Century."

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