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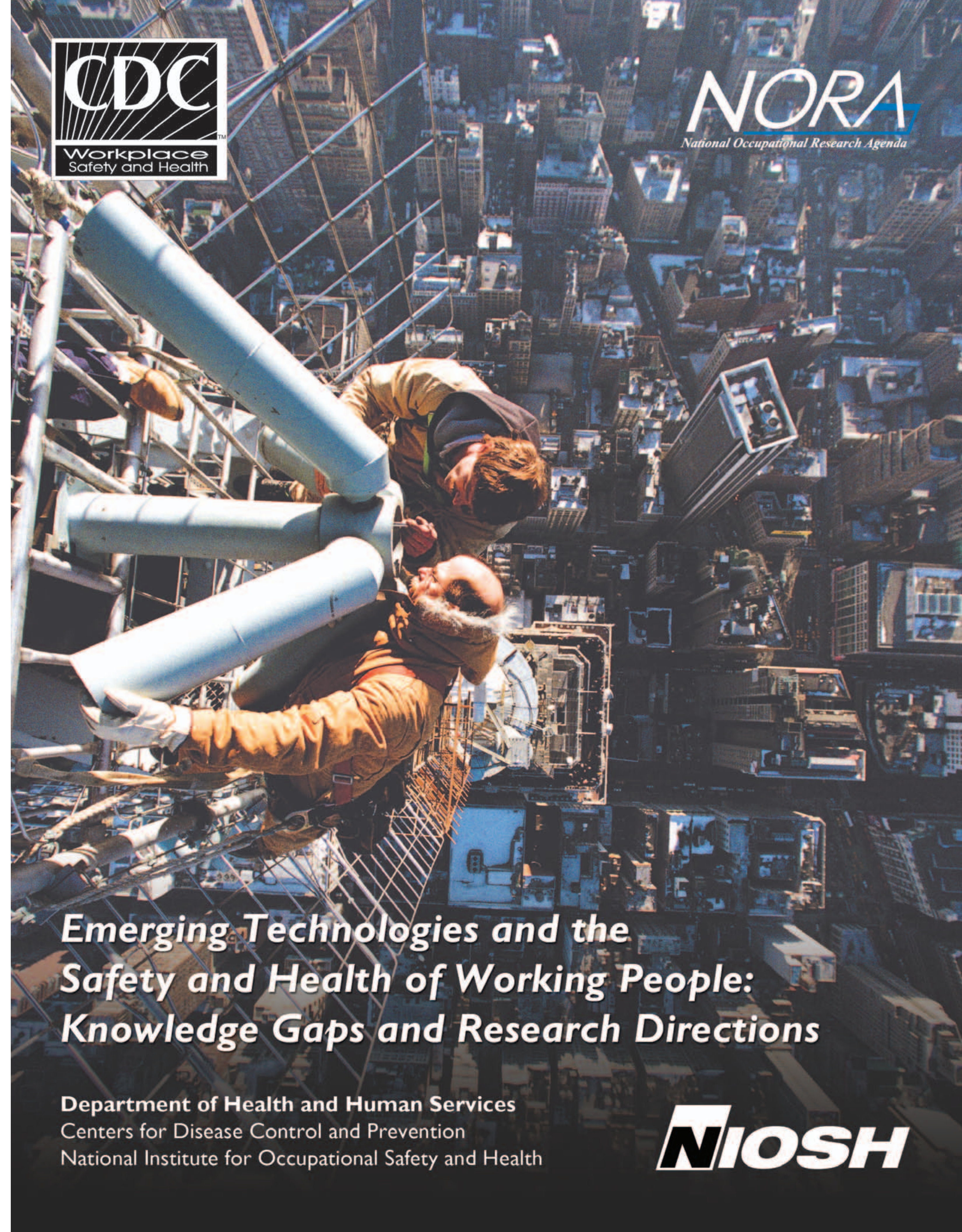

Emerging Technologies and the Safety and Health of Working People: Knowledge Gaps and Research Directions

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

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Notes

EMERGING TECHNOLOGIES AND THE SAFETY AND HEALTH OF WORKING PEOPLE

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Internet Links for the Discovery of Emerging Technologies

http://pubs.acs.org/cen/—Chemical and Engineering News, covers the chemical enterprise including emerging technologies.

Occupational Safety and Health Information Services

http://www2.cdc.gov/hhe/hheresult.asp/—NIOSH Health Hazard Evaluations

http://www2.cdc.gov/nioshtic-2/Nioshtic2.htm/—NIOSH information system that includes journal article and government document abstracts.

http://www.cdc.gov/niosh/pdfs/97-119.pdf/—NIOSH Registry of Toxic Effects of Chemical Substances (RTECS) http://nctn.hq.nasa.gov/—The NASA Commercial Technology Network gives insight into the latest technologies developed by NASA.

http://technology.larc.nasa.gov/—The NASA Tech finder is a good site for investigating new NASA technologies.

eng-eec@nsf.gov/—Industry/University Cooperative Research Centers provides information on Model Partnerships, Engineering Education and Centers, Division Directorate for Engineering, National Science Foundation.

http://www.dhs.gov/dhspublic/theme_home5.jsp—U.S. Department of Homeland Security identifies research and technology at the cutting edge.

Science and Technology Information Services

http://www.technologyreview.com/—The MIT Technology Review is a source for detailed discussions of emerging technologies.

http://www.globaltechnoscan.com/current-issue.htm—Weekly magazine on New Technology at the Global Technoscan site keeps up with new developments in technology.

http://scitechdaily.com/—SciTech Daily is a convenient source of cross-disciplinary news for all areas of science and technology. Particularly useful are the links to many other Sci-Tech news sources on the lower left hand column of the page.

http://www.sciencedaily.com/—Another excellent source of links to daily science and technology news.

http://www.eurekalert.org/—The American Association for the Advancement of Science's (AAAS) science news website.

http://www.sciencemag.org/—Science Magazine is the AAAS's chief publication, which has many articles online in PDF format.

http://www.nature.com/—Nature, the UK's equivalent to Science Magazine

http://www.darpa.mil—Technology Transition describes technologies that DARPA has developed for the Armed Services.

http://www.americanscientist.org/—American Scientist, published by Sigma Xi, contains many full text articles.

http://www.economist.com/science/—The Economist, Technology and Science section including their Technology Quarterly, which solicits newsworthy candidates for emerging technologies.

Foreword

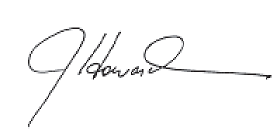
Throughout its 34 years as the Nation's primary research agency for worker safety and health, NIOSH has played a vital role in improving safety and health in the workplace. However, much remains to be done, and new challenges are always on the horizon. Without question, this is the case with the emerging technologies.

Since its inception, NIOSH has been committed to understanding and preventing hazards arising from emerging technologies. In the 1970s, NIOSH investigated issues related to emerging technologies including X-ray use at airports, new glues used in construction, new plasticizers and chemical additives used in manufacturing, and radiation and ergonomic issues related to the use of video display terminals in offices. In the 1980s, NIOSH investigated the injury hazards of robots, the biohazards related to the care of patients with emerging infectious diseases, increased dust exposure related to the longwall mining technology, and the indoor air contamination related to tight building technology. In the 1990s, NIOSH launched studies of the potential hazards with electromagnetic radiation and falls from elevations relative to erecting and maintaining communication towers, of new fiber manufacturing technology, and the consequences of potential skin and respiratory exposures during the manufacture of new drugs.

Emerging technologies offer challenges and opportunities with regard to worker safety and health. This entails a shift from retrospective analysis to a prospective analysis. Anticipation of risk and benefits is part of this new perspective as is the need to rethink the design process for technologies and their production, use, distribution, and disposal. In addition, a knowledge driven focus aimed at designs that eliminate hazards from emerging technologies, as well as encouraging technologies that are inherently safer, is needed.

In 1996, the National Occupational Research Agenda recognized emerging technologies as one of 21 priority research topics for the next decade, and a multidisciplinary team of researchers and practitioners from government, industry, labor, and academia was assembled to craft the research agenda presented in this report. Moreover, the first emerging technology to be addressed using the systematic approach proposed in this report is applications of nanotechnology, which is consistent with the National Nanotechnology Initiative Strategic Plan published in December of 2004.

We are confident that these measures will serve to energize urgently needed research on safety and health in the changing workplace. I commend to you the present report—not as a final definitive statement on research needs, but as a framework for a national agenda to elevate emerging technologies research to a higher priority in occupational safety and health, to provide guideposts for research direction, and to develop partnerships in support of these pursuits.



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Appendix: Internet Links for the Discovery of Emerging Technologies

Websites Focused on Emerging Technologies and the Study of the Future

http://nanodot.org/topics.shtml—The Foresight Institute's nanodot.org website has "News and Discussion of Coming Technologies" organized into topics

http://www.oricomtech.com/emerge.htm—Oricom Technologies website has organized set of links to emerging technologies

http://josephcoates.com/resources.html—Joseph Coates' website has a list of links to Future Studies resources, including think tanks and organizations, university programs, and government sites

http://www.theatlantic.com/unbound/flashbks/computer/tech.htm—The Atlantic Monthly's "Prophets of the Computer Age" links to two articles that predicted the future of computing technology

http://www.techreview.com/—Technology Review from MIT monitors emerging technologies.

Search Engines for Locating Emerging Technologies

http://www.teoma.com/—Teoma's Advanced Search pages allows optimization of search results

http://www.google.com/—Google's Advanced Search page allows optimization of search results

http://www.scirus.com/—Scirus is labeled as a search engine "for scientific information only" but it includes science and technology

Government Technology Resources

http://dtica.dtic.mil/index.html—The Defense Technical Information Center's Manpower and Training Research Information System is one of many emerging technology websites (see http://www.dtic.mil/)

http://www.uspto.gov/patft/index.html—The US Patent and Trademark Office's website offers free online patent searches to those who are willing to wade through the odd language used in patents

http://www.federallabs.org/—The Federal Laboratory Consortium for Technology Transfer aims to aid the rapid integration of research and development resources within the mainstream of the U.S. economy.

http://www.autm.net/scripts/TTOffices/showunivoffices.cfm—The Association of University Technology Managers (AUTM) lists University Technology Transfer Offices can be a starting point for finding university-developed technologies

Abstract

Changes in technologies have far outpaced our knowledge about the implications of these changes for the quality of working life and for safety and health on the job. This gap in knowledge is one of the 21 priority areas for research under the National Occupational Research Agenda (NORA)—a framework crafted by the National Institute for Occupational Safety and Health (NIOSH) and its partners to guide research into the next decade. This report was developed under NORA as a foundation for a comprehensive research agenda for investigating and reducing occupational safety and health risks as well as intervention opportunities associated with emerging technologies. Research and development needs identified in the agenda include (1) improved surveillance mechanisms to better track the emergence of technology, (2) accelerated research on safety and health implications of emerging technology, (3) increased research focus on protecting and promoting safety and health in emerging technology fields, and (4) steps to formalize and nurture emerging technology as a distinct field within occupational safety and health.

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Executive Summary

While emerging technologies can potentially create or transform industries, their development has far outpaced our understanding of their implications for occupational safety and health. Applications of emerging technologies may pose new hazards to workers or they may offer solutions to eliminate or reduce current workplace risks. This report focuses on four areas of research and development needed to identify and evaluate the possible positive and negative impacts of emerging technologies on occupational safety and health.

The first need is to identify and prioritize the emerging technologies that require the most research attention. This report suggests a two-tier approach to fill the current gap in *identification and surveillance* of emerging technologies and their impact on occupational safety and health. The first tier would use existing sources of information to identify relevant emerging technologies. The second tier would prioritize which applications of these technologies could potentially harm or benefit occupational safety and health. Surveillance needs include:

- Knowing the minimum data needed for the identification and surveillance of emerging technologies;
- Recruiting academic experts to evaluate emerging technology literature for potential negative and positive consequences for occupational safety and health;
- Developing methods for effective early screening of emerging technologies;
- Training developers of new technologies to identify both potentially risky technologies and technologies of value to occupational safety and health;
- Convening consortia around priority technologies to consider their potential for application and concerns regarding worker safety and health;
- Increasing funding and awareness to enable technology developers to appreciate the perspective of occupational safety and health experts and encourage them to develop applications that will improve safety and health in the workplace.

Another need is to develop an iterative risk assessment process to assess new and emerging technologies. A standard risk assessment framework could be adapted to assess emerging technologies' potential safety and health risks and benefits. This analysis would be based on continuous iterations that build upon current knowledge and informed by findings from targeted research. This proposed framework would contribute to worker safety and health by better understanding the hazards and benefits posed by the production, distribution, use, and disposal of the products of emerging technologies. Research needs include:

- Investigating the use of a risk benefit analysis that would apply an iterative, prospective assessment framework during all stages of a technology's development;
- Identifying research gaps while iteratively analyzing new and emerging technologies so that critical needs can be filled via research agendas for specific new technologies;

- Developing tools for analyzing the hazards and benefits posed by emerging technologies on worker safety and health;
- Developing methods to test technologies at their development stage for potential hazards, which may lead to redesign;
- Developing evaluation criteria that deal not only with hazards but benefits of emerging technologies;
- Developing new methods to analyze the costs and benefits of new technologies.

Third, a new way of thinking about the design of emerging technologies and their deployment is needed that would result in safer workplaces. This new approach needs to consider inputs, products, and processes that are inherently safer for the worker. The focus is on eliminating the hazards rather than controlling them. Research needs include:

- Extending the emphasis on inherently safer principles, currently in wide use in the chemical manufacturing industry, to other sectors such as agriculture, construction, transportation, healthcare, and services;
- Building the foundations of inherently safer processes through scientific research and the translation of research results into practice;
- Developing methods to prospectively identify benign emerging technologies that can substitute for traditionally risky technologies;
- Developing methodologies to measure the degree of inherent safety for the comparison of alternative designs;
- Recognizing that emerging technologies, which are designed to improve the environment, should also improve occupational safety and health;
- Sharing expertise with technology developers so that new applications will either enhance occupational safety and health or at least be introduced safely in the workplace;
- Overcoming barriers in improving workplace conditions, while maintaining high-quality and innovative products or services;
- Informing applied science and engineering professionals of inherently safer design needs;
- Developing methods to interpret data and information upon which technologies are evaluated;
- Increasing receptivity to inherently safer design needs.

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Finally, it is important that we create an integrated process for adopting beneficial emerging technologies and avoiding potential safety and health problems with these technologies. This process needs to integrate the identification, analysis, and design of emerging technologies. It must also encourage collaboration between safety and health professionals and technology developers. Research needs include:

- Investigating opportunities for using information technology or electronics and communications to monitor and inspect workplace programs;
- Encouraging the development of specific innovative technologies to control or eliminate persistent occupational illnesses or injuries;
- Developing partnerships for identifying research needs regarding rapid changes in the nature of work and unintended consequences in safety and health associated with new and emerging technologies;
- Extending research linking emerging technologies and occupational safety and health into specific occupational environments such as the construction, agricultural, and service industries;
- Exploring government-funded research programs that can have an impact on the inherent safety of emerging technologies;
- Fostering partnerships among government, industry, and academia to develop and implement inherently safer designs and principles for more benign technologies;
- Applying the precautionary principle to emerging technologies analysis regarding U.S. worker safety and health issues.

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The challenge for identifying emerging technologies that can bring benefits or pose potential risks to occupational safety and health is both simple and difficult. It is simple to find new technologies that are emerging as economically viable, but the difficulty lies in choosing the appropriate subset of these technologies for surveillance and later analysis. The challenge is to define the minimal set of data needed to make this choice.

The identification of emerging technologies that warrant occupational safety and health interest leads to prospective analyses of the potential risks or benefits of these technologies. Occupational safety and health professionals in the United States are familiar with risk assessment, and it can be adapted for use in anticipating hazards as well as benefits. This adaptation involves acting on knowledge as it accrues about the hazards of the technology.

It also involves moving the process from a regulatory to a knowledge-driven perspective in order to expedite changes toward inherently safer options. Conversely, a new technology may be safer than a current technology, which can expand the market for the technology into the occupational safety and health niche. The analysis adds a prospective step to the risk assessment approach by asking "what if" and "what could" to the team assembled for the analysis. The challenge is for multidisciplinary commitment to teamwork in this process.

Firms developing emerging technologies may more readily accept inherently safer design principles since they have yet to invest in the production process or market acceptance of a product. Fundamentally, inherently safer design aims to avoid hazards rather than control them, and this approach is essential in selecting designs that are relatively benign for occupational safety and health. This approach can also assist in identifying technologies that could be deployed as they emerge from other sectors. A challenge is to gain universal acceptance of principles for inherently safer designs so they can be used by developers of new technologies.

The identification, analysis, and avoidance of hazards as well as identifying the opportunities for improving occupational safety and health associated with emerging technologies requires an integrated approach. This integration requires the occupational safety and health professional's involvement with the technology developers and entrepreneurs through the life cycle of new technologies. Indeed, the whole analysis team must continuously interact in order to transform the emerging technology into an inherently safer technology. The challenge is to bring the various stakeholders together in a continuous interaction so that the emerging technology can provide for the improved safety and health of working people.

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Early Reporting of Effects

New information, such as toxicological data on materials used in the manufacture of the technology, would trigger an updated prospective analysis. Because of the complexity of the emerging technology process, there is a gap in the community's ability to recognize adverse consequences of emerging technologies in their initial stages of use. Techniques are needed to evaluate the emergence of new injuries or diseases that are associated with the product or processes of emerging technologies.

Historically, a Health Hazard Evaluation technique has been used to spot such problems. This technique is an after-the-fact approach to signal unique diseases or hazards and depends on requests to evaluate mystery sicknesses or potential hazards related with a new product. The requests come from employers, employees, or government agencies. Still, this approach lacks a focus on emerging or benign technologies.

Many innovations in biotechnology and nanotechnology are expected to create new opportunities and may even offer new options in the prevention and diagnosis of diseases. Researchers need to examine areas of interest such as biotechnology or to investigate opportunities for using information technology or electronics and communications to monitor and inspect workplace programs.

Precautionary Principle

Utilization of the Precautionary Principle could be a potential approach to emerging technologies analysis. The approach was conceived in Europe and adopted as policy by virtue of the 1992 Treaty on European Union [CEC 2000]. The Precautionary Principle was defined by the United Nations Conference on Environment and Development, held in Rio de Janeiro in 1992, as follows: "[w]here there are threats of serious or irreversible damage, scientific uncertainty shall not be used to postpone cost-effective measures to prevent environmental degradation" [UNEP 1992]. While other definitions exist, the foregoing is widely accepted. In brief, the overall aim of the Precautionary Principle is to provide an approach to acting in the face of uncertainty [Grandjean 2003]. The Precautionary Principle has to date been associated primarily with preventing harm from environmental hazards, e.g., preventing the introduction into commerce of hazardous substances. However, the Principle could also be applied to the prevention of occupational injuries [Pless 2003] and workplace health problems, if adopted in the future.

Advocates of the Precautionary Principle see it as an alternative to the use of risk assessment by which to predicate risk management actions, often a lengthy, litigious, and costly process [Tickner 2003; Tickner et al. 2003]. It remains a challenge to apply the Precautionary Principle to emerging technologies analysis of U.S. workers' safety and health issues.

Conclusion

The anticipation of occupational safety and health hazards has been a tenet for safety and hygiene professionals for some time. This report provides an approach for putting this principle into action. It attempts to provide the foundation for identifying, forecasting, and avoiding hazards with technologies as they emerge into widespread use. It also addresses the opportunities for applying emerging technologies to improve occupational safety and health when they replace hazardous existing technologies. This approach can link heavy investment with inherently safer designs to protect the safety and health of workers.

Economic Consequences, and Control Technology and Personal Protective Equipment.

Research should be extended into specific occupational environments such as the construction [Transportation Research Board 2003], agricultural [US Department of Agriculture 2003], and service industries. Examples of possible research topics are:

- The integrity of new materials in building construction (structural and fire safety);
- Safer fertilizers and insecticides for food production or lawn and garden care;
- Mechanical devices and power tools to reduce ergonomic stress to workers;
- Novel protective devices against non-ionizing electromagnetic radiation.

Other NORA priority areas are linked to many recommendations in this paper. The chapter on the identification and surveillance of emerging technologies relates to *Surveillance Research Methods*, the chapter on prospective analysis relates to the *Risk Assessment Methods* priority, and the chapter regarding inherently safer design relates to the *Control Technology and Personal Protective Equipment* priority.

Government Funding

Government-funded research programs can have an impact on emerging technologies and should be a priority. An example of a beneficial technology that, through innovation, became more beneficial is the Defense Advanced Research Projects Agency (DARPA) support of research in the late 1970s and early 1980s that led to the chemical synthesis of DNA [Sprackland 2002]. This synthesis allowed researchers to bypass the need to produce DNA through direct replication, and as a result, they were able to generate much higher yields of DNA.

By 2002, a project funded by the National Institutes of Health (NIH) and DARPA had shown the promise of reducing time for the sequencing of genetic information of a person's DNA from 2 to 4 years to 24 hours [University of Houston 2002]. This new technology included the use of a genetically engineered enzyme, DNA polymerase, which sequenced bases in a DNA strand that could be read by a computer. This is an emerging area called bioinformatics in which genomics and computer technology have merged.

Coordinated Effort

A coordinated effort including government, industry, and academia is needed to optimally provide for developing and implementing inherently safer designs for more benign technologies. Government research agencies can assist firms or industries to undertake TOAs in the adoption or development of new technologies. Both industry and government must be technologically literate to ensure that the TOAs are sophisticated and comprehensive. Promotion of integrated research for occupational and environmental health in federal and state governmental agencies is needed to improve criteria development and guidelines for reducing toxic releases, injuries, and diseases through inherently safer and cleaner technologies [Zwetslot and Ashford 2003]. Furthermore, operations of key disciplines and functions such as engineering, occupational safety, industrial hygiene, and environmental practice need to be joined.

Contents

5 Integrated Approaches to Research

Developing an Integrated Research Model

The design process for emerging technologies must consider an array of safety and health areas before and after deployment. An integrated rather than a specific approach to conducting occupational and environmental health research is needed. This approach would integrate innovative engineering controls with prospective analysis to protect researchers and workers during the research and development phase. In manufacturing, the approach would integrate an intrinsic toxicity-based occupational exposure assessment of the raw materials, the intermediate byproducts, and emissions with life cycle assessment and analysis of the environmental impacts. The approach also would address potential exposure routes to other workers and to the community, and it would include an analysis of the economic and health benefits to people and society from the use of the new technology. In addition, the safety and health impact of new potential uses or misuse of the technology after its deployment must be anticipated so that injury or illness prevention strategies can be implemented.

An iterative risk assessment of new technologies would benefit from partnerships between interested parties. Parties such as government, industry, labor unions, insurance providers, and nongovernmental organizations (NGOs) could partner in order to share current data, new information, risks, and benefits identified through prospective analysis. Partnerships between government agencies and private sector entities are few, but can be achieved. An example is a research partnership between the National Institute of Environmental Health Sciences and the American Chemistry Council, wherein toxicological research is jointly prioritized and funded. Finding ways to form and sustain partnerships between parties potentially impacted by new technology is needed.

Ensuring public trust in the development of new technologies is a crucial research responsibility.

Numerous examples exist of the harm that occurs when this trust is violated. Public trust in the nuclear power industry dwindled after the Three Mile Island malfunction and Chernobyl explosion. Following the Chernobyl incident in 1986, the biotechnology industry took notice and embraced risk assessment, risk management, and a culture of expertise, which made transparency rather than secrecy a priority [Fleising 2002]. The industry allocated resources to these priorities, emphasized social responsibility, and responded to critical incidents to dispel public uncertainty quickly. The biotechnology industry's responsiveness has eased a 15-year emergence of its technology in the United States.

Research Opportunities and Responsibilities

Links with Other Priority Areas

An injury and disease prevention approach necessitates the development of specific innovative technologies to reduce or eliminate persistent occupational illnesses and injuries. This approach is consistent with several other NORA priority areas that relate to disease and injury.

Since unintended consequences in safety and health associated with new and emerging technologies may not be anticipated, partnerships for identifying research needs are desirable among researchers in NORA areas concerned with the rapid changes facing the workforce. These areas include *Organization of Work, Special Populations, Social and* implementation of inherently safer technologies. These include a need to:

- Access knowledge about inherently safer technologies;
- Apply or adapt emerging technology to specific workplaces or facilities;
- Overcome resistance to change;
- Ensure that inherent safety is implanted early in the design of emerging technologies.

Applying Science to Engineering

Green chemistry [Anastas and Williamson 1998], green engineering [Allen and Shonnard 2002], and inherently safer chemical processes [Bollinger et al. 1996] represent current attempts at filling some of the gaps for new synthetic pathways, production processes, and design as a comprehensive system, but attempts are also needed in areas beyond chemical production. In addition, progress needs to be made in methods to interpret data and information by broadening the criteria upon which technologies are evaluated.

1 The Future of Technology

Changes in technologies have outpaced our knowledge about their implications as potential risks or benefits for occupational safety and health. Traditionally, this knowledge has been created after a technology is deployed resulting in a research gap between retrospective or reactionary approaches and prospective or anticipatory investments. This report follows a public health model approach. The following chapters apply the public health process of identifying, evaluating, and controlling problems. However, the result of this effort is different, for it attempts to address public health problems before they are manifested, by identifying and prioritizing technologies and their applications as they emerge, evaluating them through knowledge-driven teamwork, and providing inherently safer design principles for more benign technological applications.

The Pace of Innovation

The impact of wireless communication, biotechnology, and nanotechnology will continue to change our lives at home and at work. Round-the-clock engineering, just-in-time delivery, and advanced tracking systems have taken business to a new level. Faster and more functional software tools for engineering and management as well as new manufacturing hardware are creating a fast response workforce. This new breed of workers must cope with the speed of information technology by analyzing and making rapid decisions throughout the day [Kessler et al. 2003].

While revolutionizing the nature of work, these technological innovations are also creating challenges and opportunities for occupational safety and health. How will new technologies be identified? How can researchers anticipate, assess, and address the potential impacts from new technologies on occupational safety and health? How can developers incorporate safety and health concerns at the earliest design or continuous improvement stages? Such questions seek to frame a national discussion about the occupational safety and health impact of emerging technologies.

What Are Emerging Technologies

Emerging technologies are defined as science-based innovations that have the potential to create a new industry or transform an existing one [Day and Schoemaker 2000]. Emerging technologies exist where the knowledge base is expanding, the application to existing markets is undergoing innovation, or new markets are being tapped or created.

This rapid technological development challenges our scientific understanding of its potential risks and benefits to worker safety and health. Risk refers to possible harm to human health that may occur both in its probability and in its potential severity, while benefit refers to something of positive value to health or welfare [Dunn and Chadwick 2002]. The need to anticipate risks is well recognized [DiNardi 2003; Toffel and Birkner 2002], and past examples illustrate the potential negative consequences of emerging technologies. These examples include asbestos insulation, off-road vehicles without rollover protection, airtight buildings, and lead in gasoline. Many workplace hazards, however, have been rendered less harmful through emerging technologies, such as the automation of hazardous jobs, scissor lifts to replace scaffolds, and the use of plastic drain pipes in place of those made from lead-joined cast iron.

Understanding Innovation Processes

Hundreds of articles and books have been published over the past four decades regarding the innovation process and its rate of diffusion [Rogers 1995]. The rate of diffusion has been narrowed to a few factors, and communities have been defined by the sequence in which they accept new technologies at different rates. The early steps in this sequence—innovators and early adopters—have been used for business strategies related to emerging technology marketing and deployment [Moore 1999]. The dynamics of deploying these emerging technologies beyond these early steps has led to strategies for mainstream acceptance in the marketplace [Moore 1995]. Understanding this process is important to linking the emerging technology field with the occupational safety and health field.

Anticipating The Future of Emerging Technologies

Past examples of emerging technologies may also forecast areas of future technological growth and their impact on occupational safety and health. Emerging technologies and their applications impact many market and industrial sectors:

Communications

Perhaps no other technological development has impacted global society as quickly or profoundly as communication technology. Within one century, communication technology has grown from the invention of the telephone to a system of wireless radio and satellite linked cable communication. This development has increased the number of sedentary workers that must rapidly analyze and respond to electronic information. Mental rather than physical workloads are now a growing concern for workers [Kessler et al. 2003].

Energy Technology

Governments and industries have made major advances in developing affordable and environmentally responsible energy strategies. Highly efficient combined cycle power plants produce electricity from natural gas. Wind turbines create electricity without fossil fuels. Fuel-efficient gasoline-electric hybrid vehicles are now commercially available, and research continues on the development of hydrogen fuel cells that can power vehicles without gasoline or diesel fuels. Despite the promise of these technologies, each involves exposing workers to new safety and health hazards such as servicing the large batteries in hybrid cars and the need to work at great heights to service wind turbines.

Transportation

Technologies to transport people, goods, and services are vital for local and national economies. The internal combustion engine currently dominates transportation technology, allowing these economic needs to be achieved while providing the benefit of personal mobility. Yet the internal combustion engine significantly contributes to air pollution. Unleaded gasoline, reformulated gasoline, (e.g., low-sulfur diesel fuel), and the use of catalytic converters have improved air quality, but concerns over global warming, resource conservation, and the health consequences of fossil fuel combustion are stimulating a search for alternative technologies. The development of a hydrogen fuel cell vehicle is intended to be a long-term solution to meet global energy and environmental requirements, but problems with the production, distribution,

its product. It may be relatively easy for the firm to find an alternative, safer process if it focuses on the ancillary process. Inherently safer designs are better received with emerging technologies in the later stages of production, although in the design-to-technology adoption process, a design freeze will need to be anticipated.

Advancing Inherently Safer Designs

Expanding Inherently Safer Designs

Most attention to inherent safety principles for workers has occurred in the chemical manufacturing sector [Hunter 1999], but these approaches need to be explored in other sectors such as agriculture, construction, transportation, healthcare, and services. Scientific research is needed to advance the foundations for inherently safer and cleaner industrial processes and to translate that knowledge into practice. Systematic analytic methodologies are needed to measure the degree of inherent safety to allow for the comparison of alternative designs. Research is needed so emerging technologies that are designed to improve the environment also improve occupational safety and health [Ashford et al. 1996]. A systems approach is needed for integrating occupational and environmental assessments into operations at the firm and corporate levels. This includes the development, validation, and dissemination of data elements and models that can be used by safety and health professionals throughout industry to support early and effective technology evaluation. Researchers also need methods to identify benign emerging technologies during the prospective analysis that can substitute for traditionally risky technologies.

Table 2. The stage of production explained by an example of casting and electroplating in metal screw manufacturing.

Stage of production	Example	Potential occupational hazards
Primary	Casting	Toxic fumes and molten metal contact
Secondary	Electroplating	Toxic and corrosive hazards
Ancillary	Cleaning or degreasing	Toxic and flammable solvents
Product	Metal screws	Injury

Integrating Inherently Safer Design into Business Practice

Experts in occupational safety and health need to attend conferences or other forums to identify workplace applications for new technologies. Such forums will also allow these experts to share their expertise with technology developers so that new applications will either enhance occupational safety and health or at least be introduced safely in the workplace. Research is needed to overcome barriers in improving workplace conditions and economics, while maintaining high-quality and innovative products or services. Firms that have succeeded in these improvements have developed strategies that enable them to thrive in the midst of change. Their example suggests a need for research strategies that identify information needs and technology gaps in order to encourage widespread development and

Robotic welding: New and advanced manufacturing systems have generally led to a safer workplace. Robotic welding in the automotive industry since the 1970s has led to higher quality products and reduced human exposures to welding fumes, ozone, UV radiation, and other hazards associated with welding (see Figure 5), but new hazards need to be avoided [NIOSH 1984]. Smart manufacturing systems with sensors to provide real time feedback to an operator have improved product quality and occupational safety and health.

In order to facilitate exposure reduction and injury prevention, researchers must articulate and evaluate technical options using multivariate criteria, which include safety and health, economic, and environmental factors. These criteria can also be used to compare improvements that each option might offer over existing technological solutions [Zwetsloot and Ashford 2003]. One approach is Technology Options Analysis (TOA), which entails the identification of inherently cleaner and safer options for the technology being considered. TOAs can identify designs that might be expanded into widespread use, technologies that might be transferred from one industrial sector to another, or benign technologies that still need to be developed. TOAs expand risk assessments to include alternative production technologies, e.g., input substitution and process redesigns [Ashford 1997].

TOAs need to be augmented by analyses that identify where in the production process changes to inherently safer inputs, processes, and products could be made. Such analyses have addressed environmental impacts, but they need to be expanded to include the occupational environment.

The Toxics Use Reduction (TUR) Institute of Massachusetts evaluated the application of TUR in OSHA programs [Penney and Moure-Eraso 1995; Roelofs et al. 2000]. It evaluated the impact on occupational health practices in 35 Massachusetts firms where the State promoted cleaner production alternatives. The study concluded that TUR activities improved the work environment, but that such improvements were neither systematically planned nor incorporated into their activities. Information about superior technologies regarding existing options to protect both workers and the environment were also missing.

An opportunity for improved occupational safety and health exists with firms that develop emerging technologies, because they are more likely to adopt more benign technologies in new facilities or operations [Zwetsloot and Ashford 2003].

New operations, which may be driven by emerging technologies, are most receptive to modifying their processes and final products. Firms in transition may delay implementing safety improvements even though they require new investments in an existing facility. Nonetheless, these firms may adopt emerging technologies with inherently safer designs if they are searching for ways to improve safety, protect the environment, or reduce high costs related to energy, water, or materials.

The receptivity to inherently safer designs differs for primary, secondary, and ancillary production processes as well as final products. These processes are exemplified in Table 2. The most resistance to innovation might be expected from existing firms whenever demands are placed on changing their primary process. When a new process is adopted, usually by the diffusion of an alternative technology, the firm may be hesitant to change a proven method and take a chance on altering the appearance of

storage, and use of hydrogen must be resolved. Since hydrogen can burn and explode, the development of hydrogen-powered vehicles will have consequences for workers who build, operate, and service them.

Food Production

The global population is expected to increase from six to nine billion people by the year 2050 [U.S. Census Bureau 2003]. Food production and processing must change to feed this growing population. Genetically modified plants, grains, and animals already exist, but the future may see even more manufactured foods. Molecular farming technology may ease global warming by eliminating the need for fermenters, but genetically modified plants may pose potential safety problems. Plants designed for their tolerance to selective and novel herbicides may result in applicator exposure to potentially harmful pesticides. Conversely, opportunities may result from genetically modified plants that are resistant to infestation and decrease the need for certain toxic insecticides.

Housing

New synthetic housing materials and novel production methods may be potentially hazardous to construction workers who have contact with substances of unknown toxicity. New technologies are needed to reduce injuries in residential construction such as falls from roofs. Finally, it is important to understand how new construction materials behave under high stress conditions. For example, emergency workers may need to change their procedures if new materials do not maintain integrity under the thermal stress and moisture levels associated with fires and fire suppression.

Medicine

The advent of molecular biology and the growth of biotechnology have revolutionized medicine and the life sciences. Biotechnology has introduced pharmaceutical uses for new protein biomolecules, while molecular biology has led to the discovery and development of new medicines and clinical diagnostic procedures. Over the last decade pharmaceutical research has been transformed into a highly industrialized process that can now achieve molecular level detail, and draws from genomics, combinatorial chemistry, and advances in microfluidics. Moreover, information technology has enabled researchers to better understand the causes, diagnosis, treatment, and prevention of disease. New drugs, however, can be toxic and may pose hazards to healthcare workers and veterinarians through prolonged exposures or unexpected toxic interactions.

Materials

The plastics revolution of the mid-20th century led to less expensive, lighter, and sturdier products such as beverage containers, clothing, automobile parts, and portable telephones. Nanotechnology is now emerging as a new means to produce strong, lightweight materials. Nanotechnology may make it possible to build items by manipulating individual atoms.

Nanotechnology presents beneficial opportunities for worker safety and health, like a self-cleaning window coating that reduces the need for workers to be suspended from a tall building to wash windows. These very small nanoparticles, however, may have unexpected properties and may present health hazards to humans. For example, the inert metal gold becomes chemically reactive at the nano-level [Haruta 2001].

Mechanized mining: Historically, the leading threats to coal miner safety and health were roof falls, methane and coal dust explosions, and coal miners' pneumoconiosis (black lung). Early mining was dangerous, physically demanding work. The industry used wooden supports, timbers, and posts to prevent the roof from falling or relied on the roof to be self-supporting, where the digging and loading of coal was done manually. The lack of mechanization and the use of wooden supports was labor intensive and ineffective, limiting productivity and the generation of methane and coal dust. A new technology, roof bolts, emerged in the early 1950's. The roof bolts were long bolts that were placed in the roof, typically on four-foot centers, to either support the lower portion of the roof strata or to cause roof strata to form a laminated beam. Roof bolts primarily prevented large roof falls, but smaller rocks still fell, and even a relatively small rock could cause a fatality. The use of roof bolts along with mechanized coal loading and cutting enabled productivity to grow and as productivity grew, so did the production of methane and coal dust. This increase of mechanization led to the longwall system, which provided full roof support using massive steel/hydraulic supports (see Figure 1). In longwall mines, coal production was so fast that gas liberation limited production. This problem was addressed by actively draining the methane from the seam before and during mining, some of which is sold to natural gas companies. Dust generation also increased and required advanced dust control technology. Longwall technology addressed the roof fall problem and increased productivity but required new methods to mitigate the safety and health issues that it introduced.

Figure 1. Improved productivity is realized with improvements in safety and health in longwall mining.

Emerging Technologies and the National Occupational Research Agenda

The National Occupational Research Agenda (NORA) arose from the recognition that occupational safety and health research in both the public and private sectors would benefit from targeting limited resources. The creators of the Agenda also recognized the need to address changes in the U.S. workplace, and NORA addresses the broadly recognized need to focus research in the areas with the highest likelihood of reducing the still significant toll of workplace injury and illness. Emerging technologies bring change to the workplace, yet through design, these technologies can reduce existing hazards.

NORA recognizes the importance of emerging technologies for occupational safety and health. A broad concurrence among stakeholders led to including emerging technologies as a NORA research priority. As a result, NIOSH established an Emerging Technologies Team to develop a research agenda that would address knowledge gaps and

Cleaner Production Technologies and the Work Environment

The relationship between environmental innovations and worker health is an important example of unintended hazards. The substitution of hydrochlorofluorocarbons for chlorofluorocarbons reduced damage to the ozone layer, but it created both a carcinogenic and flammability risk to workers. In another example, water-based paints eliminated volatile organic solvents but created a biocide hazard for workers [Ashford 1997].

Ensuring worker safety and health and environmental improvement must be seen as interrelated rather than as separate activities. Environmental concerns now are increasingly factored into design and operational decisions, but in order to further integrate the work environment, managers need to encourage scientists, engineers, and technology developers to include safety and health concerns in both their design and operational criteria. The recent occupational health literature contains a growing number of studies addressing the theory and practice of the integration of industrial hygiene and environmental preventive procedures [Armenti 2002; Roelofs 2001; Bartlett et al. 1999; Quinn et al. 1998; Enander et al. 1998; Ellenbecker 1996; Goldschmidt 1993]. Finally, a recent study of the benefits and barriers of next generation environmental technologies in a number of U.S. industries concluded that, although in its infancy, green chemistry technologies provide significant benefits for occupational health, environmental health, and economic security [Lempert et al. 2003].

The diversity of work environments, however, makes implementing such strategies challenging. It is difficult to know every organization's facility layout, degree of automation, equipment status, engineering controls, and administrative practices such as shift work [Ashford 1997].

Chemical manufacturing processes in the United States, Italy, and China, for example, range from manual reactor vessel charging, mixing, packaging, and maintenance to processes that are enclosed and automatic. The same process under these different conditions has different implications for worker safety and health. If a worker was exposed, the physiologic route of entry cannot always be anticipated, because knowledge of the physical state of the substances at different stages in the process is lacking.

Figure 5. Robotic welders in a modern automotive assembly. Note the absence of sparks and intense UV radiation. Manufacturing engineers responsible for the robotic system operate in front of a control panel that is not in view.

manufacturing matches, and thus, the elimination of the devastating disease, phosphorous necrosis of the jaw [Myers and McGlothlin 1996].

- ***Alternative reaction routes*** is a method exemplified by a change in the process used to produce the insecticide, Carbaryl, for which methyl isocyanate was an intermediate product. Methyl isocyanate was the chemical released at Bhopal, India, where approximately 3,800 people died. By using the same raw materials but changing the process by sequencing the chemical reactions in a different order, methyl isocyanate was eliminated as an intermediate product [Bollinger et al. 1996].
- ***Modified storage requirements*** keep chemicals such as ammonia or chlorine at a pressure below their boiling point where, in case of a leak, the evaporation rate would be relatively low.
- ***Energy limitation*** reduces the amount of energy available in the production process. A historical example serves to illustrate this method in preventing hazardous exposures. Gustave Eiffel, in constructing his tower in 1889—an emerging technology of his day—assembled parts of the tower on the ground to avoid exposure to falls from a high elevation on the tower. No employee lost his life while working on this project [Barry 1972].
- ***Simplification*** uses processes and facilities that are designed to eliminate unnecessary complexity and be tolerant of operators' errors. The nuclear power plant incident at Three-Mile Island in 1979 is an example of a complex process that encouraged errors [Perrow 1999].
- ***Optimal plant layout*** is an additional method which is an inherently safer design for logistical activities [Zwetsloot and Ashford 2003].

Inherently safer and cleaner technologies may result from technology-forcing performance regulations [Strasser 1997]. More than a century ago, the Safe Appliances Act of 1893 required that railroad companies use the latest safety innovations to protect their workforce, and as a result air brakes and automatic couplers were adopted nationwide followed by many other technologies that steadily reduced the rates of fatal and serious injuries to workers [MacLaury 1981; Holbrook 1939]. The resulting design principles need to incorporate intervention and prevention strategies based on safety and health research findings.

The long-range implications of the technology need to be understood to ensure that technology forcing does not shift one kind of risk into another type of risk. Moreover, all of these principles need to be considered together so as to avoid the creation of unanticipated hazards [Mannan 2002].

The investigation of candidate principles can include the results of other investigations. One of these is the Theory of Inventive Problem Solving [Rantanen and Domb 2002], which is an engineering design approach that uses 40 principles to resolve contradictions between risks and benefits. It is a tool for engineers to view problems outside of their experience and avoid tradeoffs by eliminating risks and exploiting benefits at the design stage (Altshuller et al. 1997).

research needs related to emerging technologies and reduction of occupational safety and health risks. Research and development needs identified in the agenda include (1) improved surveillance mechanisms to better track the emergence of technology, (2) accelerated research on the safety and health implications of emerging technology, (3) increased research focus on promoting safety and health in emerging technology fields, and (4) steps to formalize and nurture emerging technology as a field in occupational safety and health.

The Team Mission: (1) to anticipate the potential occupational risks of new workplace processes, equipment, materials, and work practices, (2) to assess the benefits of new technologies that can improve occupational safety and health, and (3) to identify the needed industrial changes that have inputs, processes, and products that would be inherently safer for workers without compromising the environment.

Overview

Many challenges exist in predicting the risks and benefits of emerging technologies to occupational safety and health.

Researchers need mechanisms to anticipate both positive and negative health consequences, laboratory and statistical models to predict hazards, and surveillance systems that rapidly identify worker morbidity and mortality resulting from new materials, tools, or processes. Chapters 2 through 5 of this report outline recommendations for meeting these needs.

The second chapter of this report addresses research needed to identify emerging technologies. It promotes classifying new technologies according to the risks or benefits they may pose to occupational safety and health. This classification is a systematic approach to establish priorities for surveillance and analysis.

The third chapter recommends research toward a prospective analysis framework that anticipates the potential risks and benefits associated with emerging technologies. This framework is a modified risk assessment approach that is based on accrued knowledge and targeted research findings and includes the analysis of benefits. This research methodology aims to help prevent exposure to hazards from emerging technologies in the workplace.

Chapter 4 describes research needed to yield a potentially safer design approach for new and emerging technologies to eliminate occupational hazards or reduce work-related risks and identify more benign alternatives to replace riskier technologies.

This method establishes the need for principles that consider inputs, products, and processes that are inherently safer for the work environment, such as using benign or less harmful materials.

Finally, Chapter 5 integrates the identification, analysis, and design methods so as to eliminate or reduce the risks as well as maximize the benefits of new technologies. This chapter also makes recommendations for additional collaboration in research.

4 Achieving Inherently Safer Designs

Inherent Safety

An iterative risk assessment will enable researchers to integrate safety and health throughout the life cycle of products or processes. Inherently safer technologies are intended to significantly reduce or eliminate biological, chemical, and physical hazards simultaneously, so that issues such as chemical toxicity are evaluated concurrently with explosion potential, flammability, ergonomic or injury hazards, radiation, and noise [Zwetsloot and Ashford 2003]. Inherent safety is an intrinsic feature of the design. It is best implemented early in the design process prior to huge capital expenditure and can even lead to cost savings [Mannan 2002; Christensen and Manuele 1999].

The simplification of the production process for the chemical synthesis of DNA is an example of an inherently safer design. Two principles of inherent safety—simplification and substitution—were applied to reduce the hazard and cost of bringing this technology to market. The production process underwent redesign to use fewer solvents and reagents by halving the number of steps from four to two. The use of the most highly toxic reagents and solvents was eliminated and chemical waste was reduced by 75%. Not only was safety improved, but the expense of hazardous solvent and reagent waste disposal was reduced—a cost that was equivalent to the purchase of the chemicals [Sprackland 2002].

The occupational safety and health community can play an important role in improving the evaluation of emerging technologies for inherently safer design opportunities by nurturing partnerships to pilot these approaches. It can assist firms in these tasks as well as to provide businesses, government and academia with the tools they need to partner in these efforts. For example, occupational safety and health professionals should be involved in the prospective analysis steps and iterate within the process to distinguish potential benign technologies for hazardous technologies.

How to Achieve Inherently Safer Designs

Inherently safer technologies emerge from designs that focus on the elimination of hazards from the production process rather than the management and control of those hazards. In theory the inherently safer design process is less vulnerable to failure since the hazards have been significantly reduced or eliminated [Ashford 2000]. Nonetheless, a broad array of inherently safer design methods must be considered so a technology will not create a new problem while solving another. Inherently safer design, simply defined, is one that "avoids hazards instead of controlling them" [Hendershot 1999] and involves several methods, also called principles [Hazell 2000; Hendershot 1999; Bollinger et al. 1996]. The following list describes several inherently safer design methods:

- ***Intensification*** (also referred to as minimization) involves using minimal amounts of hazardous materials so that releases are not catastrophic. While this method may lead to storing smaller quantities of a chemical, it may also result in more frequent deliveries of the chemical, and thus, increase the potential for transport spills [Mannan 2002]. This example illustrates that an array of methods must be considered, because focusing on only one method may create new hazards.
- ***Substitution*** occurs when safer materials are used. For example, the Phosphorous Match Act of 1912 led to the elimination—through substitution—of the use of white phosphorous in

switch to an LED illumination economy could cut electricity consumption by 10% worldwide saving $100 billion in electricity costs per year and $50 billion in power plant construction costs.

The change could render the existing lighting industry obsolete along with its associated hazards. It would be replaced with new manufacturing technologies for LED lights with potential hazards such as the production of gallium dioxide as well as possible nanotechnology used as reflecting devices. However, there may be a more benign technology, organic light-emitting diode, which could be produced by a process like an ink-jet printer that may displace the need for expensive LED chip manufacturing facilities [Talbot 2003].

Potential concerns of LED use include the effect of ultraviolet light on health and the possibility of eye strain related to light intensity and frequency. Conversely, benefits may include better lighting where shadows and darkness conceal hazards on the job. The social benefits are potentially enormous, and there may be occupational health benefits, but costs may vary with the risk of different technology options. Finally, there is a need for new methods to analyze such costs and benefits. These methods should ensure that worker safety and health is protected while evaluating benefits of the new technology and anticipating downstream implications.

2 Identifying Emerging Technologies

The Emerging Technology Search

Responding to the pace of innovation requires two approaches that identify new and emerging technologies and their impact on workplace safety and health. One effort would identify technologies that can improve worker safety and health. Another effort seeks to identify problems in new workplace processes, equipment, materials, and practices before they enter the workplace so they can be solved.

Identification and Surveillance Gaps

Identifying new and emerging technologies is not difficult: journals of major scientific and engineering professional societies routinely cover them (see Appendix). A cursory reading of *Chemical and Engineering News,* for example, would reveal new areas of nanotechnology (with many subfields), computational chemistry, biotechnology, and bioengineering. Also included are operation and product area reviews that cover emerging technologies such as fuel cells, coatings and paints, detergents and soaps, sensors, and chemical/product manufacturing. Even though these categories can be readily identified, they are large and general. In order for this data to be useful it needs to be further analyzed to determine possible effects on workers.

Researchers have developed many methods for recognizing if a technology poses a hazard to working people. Hazard identification is the evaluation of the adverse health effects of a substance(s) in animals or in humans. It relates to those aspects of a new technology that may have adverse effects on worker safety and health based on *current* knowledge and data. It is an attempt to forecast hazardous outcomes possibly associated with a new technology that in time could become an emerging technology. Similarly, benefit identification aims to reveal the opportunities for an emerging or expanding technology to be deployed in new ways to prevent occupational safety and health problems.

As an example, nanotechnology has emerged as a key strategic branch of science and engineering in the 21st century. The interagency working group [NNI 2004] on nanoscience, engineering, and technology stated: "The ability to image, measure, model, and manipulate matter on the nanoscale is leading to new technologies that will impact virtually every sector of our economy and our daily lives." One entrepreneur identified nanotechnology by "browsing" the journal *Science* [Lenatti 2004]. He then invested time with experts to identify the areas of nanotechnology that could turn this expertise into products for existing markets. He chose an area that could revolutionize energy technology based upon new kinds of solar cells, which had the potential to be inexpensively implanted into roofing shingles and provide electricity to the residence. This approach is a cursory form of content analysis [Janowitz 1976].

While several sources exist to identify emerging technologies, the research community currently lacks a system to prioritize technologies based on the magnitude of their potential benefits or threats to worker safety and health. Nanotechnology, for example, already has applications in many industrial, commercial, and consumer products. This technology is likely to find uses in such diverse areas as materials science and catalyst development, and in products such as ceramics, electronics, advanced coating materials, pharmaceutics, and cosmetics [Pui *et al.* 1998; Otten *et al.* 2001; Fissan *et al.* 2002].

It is difficult to conduct research on whole technologies. A focus on applications of the technology provides a way to narrow the research agenda, for technologies have long been defined in terms of application, i.e., systematic applications of organized knowledge to practical activities, especially productive ones [Ayers 1969]. Indeed, the application view has produced success in the market that has driven the emergence of technologies [Moore 1999]. Knowledge about the consequences of prior applications of one technology can be predictive of that technology's impact in other uses.

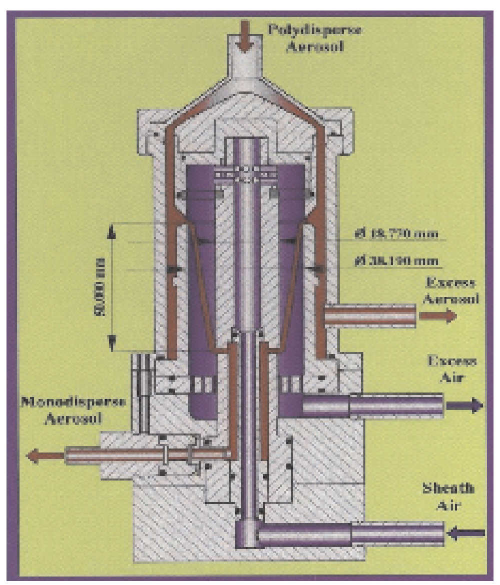

Figure 2. The nanoparticle-DMA (differential mobility aerosol) is a new instrument for the classification of nano-sized particles in the 1-50 nm range.

Responding to Identification and Surveillance Gaps

Knowing the minimum data needed for the identification and surveillance of emerging technologies like nanotechnology is critical for the research process. Researchers need to (1) identify major areas of emerging technologies, (2) survey the current state of technology within each of these areas, and (3) continue to review the areas in order to set priorities for attention or for more concerted research. Criteria are needed for minimal information identification, and a method is needed for recording this information in one or more databases. Methods also need to be developed for the identification and systematic surveillance of emerging technologies that may lead to research of their positive or negative consequences to occupational safety and health. These methods need to include criteria as well as reporting protocols for systematic surveillance. Model approaches may be adapted from other organizations [U.S. Department of Agriculture 2003; Transportation Research Board 2003] and be built on hazard identification [NRC 1983; NRC 1993].

Achieving an Iterative Risk Assessment

Application of the prospective analysis framework should be conducted by risk/benefit analysts in an iterative fashion as a new technology progresses through its various stages of development. The prospective analysis process relies on the quality of data incorporated into any particular element of the framework, so improving data quality is important.

Critical Needs

Research needs will be identified while iteratively analyzing new and emerging technology. The critical needs should be filled via research agendas for specific new technologies. The following issues are consistent with research needs to improve the prospective analysis of new and emerging technologies [Stayner *et al.* 2002]:

- Toxicological methods for mixtures of substances used in production processes;
- Health and exposure surveillance systems that contain worker safety and health data on injuries and illnesses during new technology development, production, distribution, and disposal;
- Improved toxicological methods to permit extrapolation of data between laboratory animals and humans, e.g., improved physiological-based pharmacokinetic modeling;
- Epidemiological investigations of workplace injuries and illness patterns as emerging technologies are deployed;
- Methods to measure exposure to or contact with novel materials;
- Methods to measure biological uptake of workplace materials and substances;
- Improvements in current technologies, e.g., exposure monitors, to assess exposure or contact with hazardous materials or equipment.

Analytical Techniques

Researchers need tools for analyzing hazards and advantages to worker safety and health associated with emerging technologies. These tools include methods to test technologies at their development stage for potential hazards, which may lead to redesign. In addition, evaluation criteria are needed that deal not only with hazards but with the potential occupational safety and health advantages of emerging technology. Methods need to be more cost-effective to reduce the expense of testing and analysis as well. Techniques are also needed to assure that both positive and negative consequences upstream and downstream of technology deployment, e.g., suppliers, are considered.

Cost and Benefit Analysis

Research is needed for developing new methods to analyze the costs and benefits of new technology. The conventional approach is to apply economic principles to calculate monetary estimates of benefits, but other approaches—perhaps qualitative approaches—are needed to value the benefits of emerging technologies. The analysis needs to extend beyond costs to benefits of the new technology to people and society.

An example of this need is to better understand the costs and benefits of light-emitting diodes (LED), which have the potential of moving from a niche market of LED screens and other low-light intensity applications to replacing the $40 billion incandescent and fluorescent lighting industry. The

Table 1. Continued from previous page.

3. Dose (contact) response assessment • Should biomonitoring of workers be instituted for the presence of novel toxicants? • Is research needed to assess the nature and time course of toxicant exposure?
4. Risk and benefit characterization • After consideration of hazard and exposure data currently available, are there enough data to identify workplace safety and health hazards? • Are particular groups of workers at increased safety and health risk and if so, which groups and how? • Should an injury and illness surveillance system be considered for workers? • Do benign or less hazardous production processes exist that would reduce worker safety and health risks? • What benefits to workers will result from production, distribution, installation, and maintenance of home fuel cell power systems? • Given potential sales of the fuel cell system, can economic costs and benefits be estimated with current data?
5. Prospective assessment • Will waste management of the fuel cell cause long-term environmental problems? • Would increased methanol production increase safety and health hazards to workers?

4. Risk and Benefit Characterization

The fourth step is to separate significant from trivial risks using information gathered in the preceding steps. This step characterizes a new technology with current information and corresponds to estimation and its uncertainties, probability, frequency, and severity of the known or potential adverse effects [CEC 2000]. The principle knowledge gaps that need to be addressed in this step are the uncertainties. When the available data are inadequate or inconclusive, a prudent approach to safety and health would be to assume the worst-case. This approach exaggerates the risk, but it assures that the risk will not be underestimated [CEC 2000]. It may also exaggerate the benefits for which gaps in knowledge may need to be filled before proceeding with a novel application of a technology. Table 1 shows possible questions related to risk and benefit characterization concerning our case example.

5. Prospective Assessment

This step extrapolates beyond what is known about a new technology and attempts to forecast future risks and benefits. It is an attempt to go beyond current information and data in order to answer "what if" and "how could" questions. It is an attempt to identify and prevent future problems in workplaces before they occur as well as the potential for emerging technologies to reduce or eliminate occupational safety and health problems. Prospective assessment can be embedded in the other four steps of the prospective analysis, but making it a separate element emphasizes the importance of prospective thinking and analysis. Table 1 shows examples of the questions related to prospective assessment of our case example. Prospective assessment is an adaptation of scenario analysis used in technology forecasting, but other forecasting techniques can be adapted as well [Day and Schoemaker 2000].

Nanotechnology: With the rapid development of nanotechnology, research on the potential health effects of exposure to nanoparticles on occupational and environmental health has gained increased attention. New scientific instruments to characterize nanoparticles are essential to enable this research. The nano-differential mobility aerosol (DMA) analyzer for nanoparticles is such an example (see Figure 2). Since it has been hypothesized that nanoparticles may readily enter the interstitial spaces of the lungs, preliminary studies with inert particles of nanometer size have shown an inflammatory response in some animals [Wichmann et al. 2000: Oberdörster et al. 2000]. Further research has to be conducted to establish the etiological or epidemiological basis to support the findings in the animal studies [Pui et al. 1998]. Moreover, fine particulate matter exposures have been associated with increased cardiovascular disease [Pope et al. 2003]. However, it should be noted that the nanoparticles in the atmosphere have relatively short half-lives due to their reactivity [Zhu et al. 2003], which is critical in the evaluation of the overall impact of nanoparticles in the workplace and the environment.

Addressing identification and surveillance gaps requires a range of expert perspectives. An academic expert or a team might, for example, be recruited biannually to evaluate emerging technology literature for potential negative and positive consequences on occupational safety and health. Industrial hygiene or safety professionals could then generate lists of emerging technologies and evaluate them for their potential hazards or benefits to worker safety and health and publish reports describing their potential consequences.

Methods are needed for effective early screening of emerging technologies. A matrix approach as is used in competitive technology intelligence techniques [Coburn 1999] is one strategy experts can use for translating general opportunities and concerns about emerging technologies into specific areas for surveillance.

In this method, various technology areas would be arrayed in a 2 x 2 matrix as shown in Figure 3, depicting high versus low benefits of intended use against high versus low risks to worker safety and health.

		BENEFITS OF USE	
		HIGH	LOW
Risk to Workers	High		
	Low		

Figure 3. Matrix for setting priorities for safety and health surveillance.

Those technologies offering high benefits (e.g., the high strength and light weight of carbon nanotubes) but potentially high risks to worker safety and health (e.g., possible respiratory challenges from nano-sized particle exposures) would be identified for surveillance.

Researchers can also apply this matrix to the technology's benefits rather than its risks to worker safety and health. For example, titanium dioxide coating on windows, a new nanotechnology, is self-cleaning and may reduce a window washer's risk of falls from scaffolding on high-rise buildings [Spice 2002].

A cross-disciplinary approach between occupational safety and health experts and new technology experts can facilitate the identification and surveillance process. There is also a need to train developers of new technologies to identify potentially valuable or risky technologies. Consortia need to be convened around priority technologies to consider their potential for application or their potential concerns regarding worker safety and health. Increased funding and awareness may be necessary to enable technology developers to appreciate the perspective of occupational safety and health experts and to encourage them to develop applications that will improve safety and health in the workplace.

This step identifies those aspects of a new technology that may have adverse effects on worker safety and health based on *current* knowledge and data. This is an attempt to forecast either beneficial or hazardous outcomes associated with a new or emerging technology. Table 1 shows examples of the questions that could be asked related to hazard and benefit identification in our case example of fuel cell technology.

2. Exposure or Contact Assessment

The second step uses *current* information to evaluate the probability of workers' exposure to or contact with a new technology. *Exposure* pertains to biological, chemical, and physical (e.g., radiation, noise) agents. *Contact* pertains to mechanical systems, such as equipment used in manufacturing processes. Apart from information on the agents themselves (source, distribution, concentrations, characteristics, etc.), there is a knowledge gap on the probability of contamination or exposure of the population to the hazard. Table 1 shows examples of the questions that would be asked related to exposure or contact assessment regarding our case example. The analysis also needs to address potential environmental impact and exposure routes to other workers and in the community. It needs to assess potential hazards of the raw materials to include the intermediate byproducts and emissions during the manufacturing process.

3. Dose (Contact) Response Assessment

The third step consists of using *current* information to determine the nature and magnitude of the adverse or beneficial effects to worker safety and health that would be potentially associated with a new or emerging technology. It is at this stage that researchers would attempt to identify the effect of the technology on worker safety and health. Table 1 shows examples of the questions that would be asked related to the dose (contact) response assessment in our case example.

Table 1. Questions associated with prospective analysis of a hypothetical fuel cell technology.

1. Hazard or benefit identification

- What is known about the toxicity of the resin in the fiberglass material and the electrolyte film?
- Are there elements in the production processes, e.g., hand lamination of fuel cell cases, that could be a safety or health hazard to workers?
- Does life cycle analysis of the fuel cell assembly suggest hazards to factory, transportation, or waste disposal workers?
- Would the presence of methanol pose hazards to workers who install and service the fuel cell system?
- Would the transportation of methanol from distribution points to households require alternative delivery systems, given the flammability of methanol?
- Are there hazards to homeowners from the onsite storage of methanol?
- What are the knowledge gaps and research needs?

2. Exposure and contact assessment

- Do production processes of the fuel cell assembly expose workers to any toxicants?
- Do assembly processes bring workers into contact with biomechanical hazards?
- What are the potential sources of worker exposure to methanol?

Benefits Assessments

Benefits assessment is another approach to research. Federal agencies, for example, often conduct cost and benefit analyses of proposed regulations to estimate the dollar cost and the benefits of proposed regulations. Benefits analysis applies to emerging technology research through the concept of beneficence. Beneficence addresses a nondollar value, such as protecting research study volunteers from a qualitative perspective [Dunn and Chadwick 2002]. Benefit relates to the positive value to health and welfare. Emerging technologies also provide potential benefits to occupational safety and health by eliminating or reducing traditional workplace hazards, especially those hazards that have been persistent and pernicious.

Creating a Framework for Analysis

Risk assessment, spiral development, and benefits analysis enable researchers to create a framework for analysis. This framework includes a five-element assessment of both the risks and benefits of emerging technologies. It focuses on prospective, not retrospective, analyses of emerging technologies.

The five steps would be synthesized from those of the National Research Council [NRC 1983; NRC 1993] and the Commission of European Communities [CEC 2000]. The steps are hazard or benefit identification, exposure or contact assessment, dose (contact) response assessment, risk and benefit characterization, and prospective assessment. The first four steps follow in order, but prospective assessment is woven within these steps as well as culminating at the end of the analysis. The following *hypothetical* case example will be used to illustrate knowledge gaps that need to be addressed in each step.

Case Study of a Fuel Cell

An inventor has designed an efficient, moderate cost, methanol-powered fuel cell that will generate enough electricity to meet the needs of individual households. The fuel cell produces electricity from a chemical reaction that is less polluting than conventional powerplant combustion of fossil fuels. Both oxygen and hydrogen are needed for this chemical reaction. While oxygen can be supplied directly by forcing air through the fuel cell, hydrogen cannot be supplied directly because it is difficult to store and distribute in its pure form [Burns et al. 2002]. A solution to this problem is to use a device called a reformer to extract hydrogen from alcohol fuels, which are much easier to store.

The inventor's new design incorporates novel materials in the fuel cell. A proprietary resin-hardened fiberglass case provides a durable, lightweight enclosure, and a new, highly efficient thin film forms the electrolyte for the chemical reaction. Given these construction details and the intended home use of the fuel cell to generate electricity, a prospective analysis could include the following considerations:

Five Steps

1. Hazard or Benefit Identification

The first step in the analysis is hazard or benefit identification, which was addressed in the preceding chapter, Identifying Emerging Technologies.

3 Anticipating the Impact of Emerging Technologies—the Need for Iterative Risk Assessment

Unintended Consequences of Emerging Technologies

Many emerging technologies have unintended consequences. Wireless technology, for example, has improved communication but significantly increased the weekly working hours for a growing segment of the workforce. The traditional 9-to-5 workday is rapidly changing as we are transformed by a 24-hour/7-day extended workweek with many people bonded to their electronic tools and gadgets even while they are commuting [Gleick 1999]. The risks, benefits, and psychosocial impact on workers coping with new communication devices and technologies in the new workplace should be understood [NIOSH 2002]. Driver distraction from cell phone usage, for example, has been associated with automobile crashes [Redelmeier and Tibshirani 1997].

In order to anticipate and plan for unintended consequences, innovative safety and health research must be conducted together with the development and deployment of emerging technologies. Safety and health benefits should then be communicated to consumers and workers to gain confidence and market acceptance of new devices. Research on early interventions may include, but is not limited to, the following:

- **Extended/unusual work hours:** The physiological and psychosocial impact on workers coping with longer working hours and new communication devices and technologies should be understood and proper interventions suggested.
- **Systems safety design:** Increasing awareness of inherently safer products and processes is essential so inventors and designers can focus on both technical feasibility and occupational and environmental health when developing new technologies.
- **Engineering control technology:** A review of all the materials and their intrinsic toxicity during the initial research stage should enable a comprehensive safety and health assessment of a new manufacturing process to reduce exposures to chemical and physical hazards. Innovative engineering controls of emissions in the manufacturing system that use new technologies and materials are possible.
- **Life cycle assessment:** A product life cycle approach to examine emissions and disposal issues should be considered to reduce the impact of toxins released to the environment. The analysis also needs to address environmental impacts of the product and manufacturing process. A prospective analysis needs to include protection of researchers and workers during the research and development or pre-manufacturing stages.
- **Socioeconomic benefits of new and emerging technologies:** A socioeconomic analysis, ranging from increased productivity for a particular production process to a new and sustainable economy as a result of a new or emerging technology, promotes and stimulates the research and development of new technologies.

Importance of Prospective Analysis of Emerging Technologies

Before making heavy investments in new technologies, a prospective analysis is needed to reduce the risk of emerging technologies to workers. This prospective analysis would continually iterate on the basis of current and accrued knowledge, such as potential benefits of the new technology and findings from research aimed at preventing worker exposure to or contact with hazards in the workplace.

As a result, worker safety and health may be improved by replacing hazardous technologies with emerging technologies that are benign or less hazardous through approaches such as technology options analysis, which will be discussed in the next chapter.

Automotive airbag: The automotive airbag is a case history of emerging technology. The initial design of an argon-based airbag system in the early 1970s was unacceptable since the noise levels exceeded 180 dB. An improved system using sodium azide as a pyrotechnic propellant was developed, but concerns with its intrinsic toxicity were raised. Initial reception by the public to the airbags installed in a small fleet of test vehicles in the early 1980s did not lead to market success. Meanwhile, research to reduce emissions from airbags continued [Chan et al. 1989] and thereby the responses to airbag effluents in asthmatics [Eschenbacher et al. 1991] were studied in anticipation of mass production. After the mandate of airbags for all passenger vehicles in 1994, numerous investigations on the engineering design and health impact of airbags followed. New specifications of the gaseous and particulate emissions from the airbag after deployment were required to ensure minimal health risks to the occupants.The timely safety and health research in the airbag industry has proven to be beneficial, while the potential risk with the disposal of sodium azide was dealt with by first igniting the propellant. New airbag propellants no longer contain sodium azide.

Numerous illustrations exist that highlight the importance of prospective analysis to worker safety and health. For example, a comprehensive assessment of the emissions and noise from a thermal metallic spray process at a pre-production facility for metallic coating reduced the multiple hazards at the developmental stage of a new, low risk manufacturing process [Chan et al. 1995a]. Similarly, the development of environmentally friendly refrigerant technology for mobile air conditioning systems resulted in the choice of the least toxic lubricant that was compatible with a new non-ozone depleting refrigerant (R134a). This decision was based on research findings from the exposure assessment of polyoxyalkylene glycol aerosols for a worst-case scenario [Chan et al. 1995b]. By including safety and health research early in the research and development (R&D) stage, researchers could assess the potential health impact of the emerging technologies and ultimately avoid or reduce their occupational health risks as the technologies move into production.

Research Approaches for Analyzing Emerging Technologies

Risk Assessment

Researchers need a framework to analyze emerging technologies for their risk and benefits to occupational safety and health. Risk assessment is the most accepted framework in the United States for assessing workplace and environmental hazards [NRC 1983; NRC 1993], although alternate methods exist such as technology assessment [Day and Schoemaker 2000], expert opinion [Fouke et al. 2000], or approaches such as the Precautionary Principle [CEC 2000]. Risk assessment uses

research results that can also identify new research needs and be expanded to analyze an emerging technology's potential benefits. Risk assessment can be expedited in an atmosphere of scientific discourse and consensus.

Moreover, this approach is substance-specific, and conducted only once and perhaps updated years later. Risk assessment as a tool for regulatory analysis has become time-consuming and litigious. A focus on accrued knowledge, not on regulation, would allow the analysis to be done quickly.

Emerging technologies may actually increase the cost-effectiveness and timeliness of risk assessment. For example, the emerging technologies of genomics and proteomics have been identified as breakthroughs in the evaluation of biological response and susceptibility to environmental exposures. The application of these technologies to toxicology is called toxicogenomics and has the potential benefit of linking exposures to underlying disease mechanisms and providing speedy and reliable screening of genes and their responses to exposures [Toraason et al. 2002; Iannaccone 2001]. For a prospective analysis, the traditional four-step risk assessment approach will be expanded with an additional prospective assessment step. In addition, the analysis incorporates ongoing iterations of knowledge input during the analysis and expedites the process with a focus on accrued knowledge rather than regulation.

Spiral Development

The research community needs an approach that continually updates the design of new and emerging technologies with current information as it is produced. An iterative risk assessment is one prospective framework to analyze new and emerging technologies, and spiral design is one such iterative research strategy. Developed by the U.S. Department of Defense, spiral design uses iteration throughout the analysis. It is based on current and accrued knowledge and is continually updated by research findings. Spiral development reduces risk by identifying problems early in the engineering process through an evolution that delivers knowledge in increments. (See Figure 4 for a conceptual depiction of the value of this approach.) This method allows for changes in the defined requirements as the technology matures towards its design concept, such as the need for improvements to abate or eliminate risks that are recognized in the beginning of the technological development [Farkas and Thurston 2003].

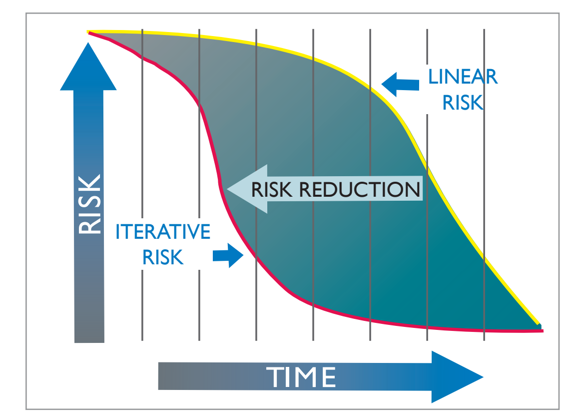

Figure 4. Risk profile comparison using an iterative rather than a linear process. Source: Software Engineering Institute.