Emerging Technologies

Inherently safer designs

By Melvin L. Myers

THE U.S. HAS WITNESSED sweeping technological changes during the last century. In the book, *Megatrends,* Naisbitt (1984) identified an explosive transformation from an industrial to an information society. He observed that technology accelerates change by expediting the time needed to communicate information.

Earlier, Toffler (1970) in *Future Shock* described technological changes in three stages: 1) a creative and feasible idea; 2) the practical application of the idea; and 3) the diffusion of the idea through society. Such creative ideas breed new ideas, and with time and technological growth, the cycle becomes shortened and change is accelerated. Naisbitt also called technology—the systematic application of organized knowledge to practical activities (Ayres, 1969)—a great engine fed by the fuel of knowledge. With exploding knowledge, technological change was accelerated further.

The workplace continues to change rapidly. This change is different from the information technology revolution of the 1990s and is expected to be more profound with a synergy of biotechnology, nanotechnology, robotics and artificial intelligence (Nygren, 2002).

One challenge is the timely identification of emerging technologies in order to anticipate, assess and address the potential impacts on worker safety and health, and to incorporate safety and health concerns at the earliest design stage. In response to this challenge, NIOSH has published its document, *Emerging technologies and the safety and health of working people.*

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This challenge was addressed in 1996 when NIOSH and its partners unveiled National Occupational Research Agenda (NORA) as a framework to guide workplace safety and health research. A broad concurrence among stakeholders led to including emerging technologies as a NORA research priority. Accordingly, NIOSH established a team to develop a research agenda to address knowledge gaps and research needs related to emerging technologies. The team set three goals:

1) Anticipate potential occupational risks of new workplace processes, equipment and material.

2) Assess the benefits of new technologies that can improve occupational safety and health.

3) Identify the needed industrial changes that have inputs, processes and products which would be inherently safer for workers without compromising or transferring problems to the environment.

Emerging technologies may spring from a new technology or a new application of an existing technology and are defined as science-based innovations that have the potential to create a new industry or transform an existing one (Day & 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.

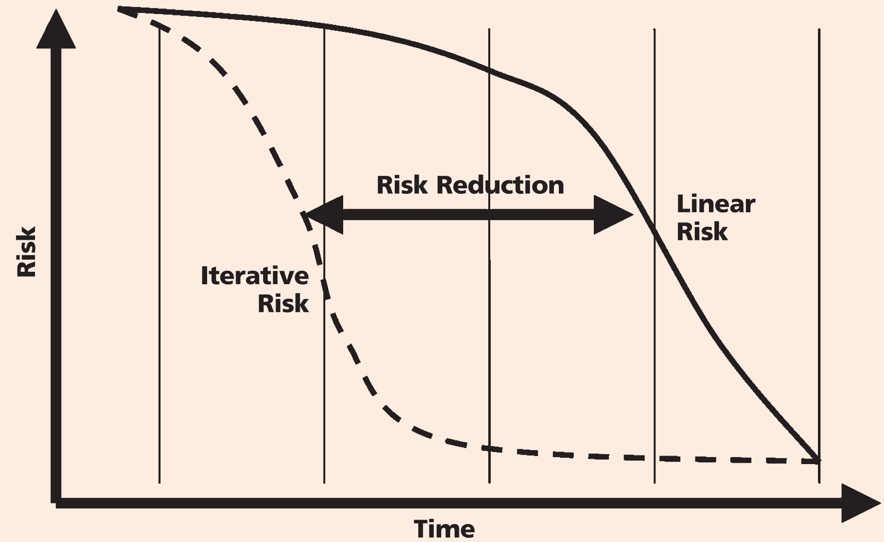
This article describes a new approach to analyzing emerging technologies for occupational safety and health consequences—both positive and negative. Four sections are presented. First, a method for streamlining the analysis process is described; second, a revised risk assessment into a prospective analysis process is explained; third, the application of inherently safer design principles is described as a way to eliminate or reduce hazards during technology development; and fourth, future directions for analyzing emerging technologies and applying inherently safer design principles are addressed.

Streamlining Risk Assessment

Risk assessment is an accepted framework in the U.S. for examining workplace and environmental hazards. Risk is defined as the combination of the probability and consequence of a hazard (Bahr, 1997). National Research Council (NRC, 1993) defined risk assessment as "the characterization of the potential adverse health effects of human expo-

Figure 1

Risk Profile that Compares the Iterative to the Linear Process



sures to environmental hazards." OSHA uses risk assessment to develop permissible exposure limits for toxicants already found in workplaces, but it has been driven by time-consuming regulatory action followed by litigious delay. It is a substance-specific assessment conducted once and perhaps updated years later. However, risk assessment can be performed quickly in an atmosphere of scientific discourse and consensus with a concentration on current information (NIOSH, 2005).

Risk assessment is traditionally a linear process, not an iterative process. However, an approach used in the Department of Defense named "spiral development" uses an iterative approach. This approach continually iterates based on current, accrued knowledge and is continually informed by research findings; it reduces risk by identifying problems early in the engineering process that delivers knowledge in increments (Liu, In & Jung, 2001). It provides for changes in the defined requirements as the technology matures toward its design concept and recognizes improvements to abate or eliminate risks along the way (Farkass & Thurston, 2003).

Figure 1 shows the relationship of linear to iterative risk. In a linear approach that follows a strict timeline, risk is reduced further down the life cycle of the technology as consequences emerge. However, in an iterative approach, risks and benefits are addressed as the technology develops and decisions can be made for eliminating or reducing hazards or exploiting potential benefits.

Although design-based engineering relies on an iterative, interactive process, current methods are lacking in engineering textbooks (Christianson & Rohrback, 1986). However, the attributes of spiral development lend weight to the use of an iterative risk assessment to analyze emerging technologies.

Prospective Analysis

A streamlined risk assessment model provides a foundation for a prospective analysis of emerging technologies to examine their risk and benefits to occupational safety and health. This approach is different because it analyzed technologies rather than evaluating the risks of individual agents. The word "prospective" is commonly defined as looking toward the future, and analysis refers to deducing consequences from initial conditions, attending to chains of reasoning and guarding against anything but intellectual exchange (Heilbroner & Milberg, 1995). NRC (1994) codified the four elements of risk assessment: hazard identification, exposure assessment, dose/response assessment and risk characterization. These four elements are shown with some modifications in Figure 2. Modifications include the consideration of benefits (Dunn & Chadwick, 2002) and injuries (Bailer, Stayner & Halperin et al., 1998), and continuous iterations informed by current and accrued knowledge from research. An additional fifth element of prospective assessment builds on risk assessment, incorporates these modifications and aims to forecast potential consequences of the technology, which systematically asks the question, "What if?" A companion element is inherently safer design (Hendershot, 1999). The elements in a prospective analysis are described in Table 1.

Hazard & Benefit Identification

NRC (1993) has defined hazard identification as "the process of determining whether exposure to an agent can cause an increase in the incidence of a health condition" (p. 249). Identification of emerging technologies extends beyond this definition. Emerging technologies must be identified, associated agents that may pose hazards need to be recognized and benefits must be incorporated into the process. Hazard and benefit identification is both simple and complex. It is simple to review several journals or technology magazines to identify emerging technologies. Breysse and Herbstman (2005) provided a literature review of emerging technologies similar to the content analysis conducted by Naisbitt (1984) for his book, *Megatrends.* They identified several emerging technologies that may have implications for occupational safety and health in the future, and they addressed the applications of these technologies to different industrial sectors. The result of this element is to set priorities for surveillance and analysis of emerging technologies (NIOSH, 2005a).

A more complex task remains: To identify specific applications and the information available regarding occupational safety and health for these applications. The challenge is to narrow the search so that serious real-world analysis can proceed. The ability to antic-

Abstract: *In 1996, NIOSH added emerging technologies as a research priority in its National Occupational Research Agenda. NIOSH named a team to develop a research agenda regarding the implications of emerging technologies for occupational safety and health. The team developed a method for conducting a prospective analysis of emerging technologies that is modeled after the risk assessment approach, but with the addition of benefit analysis.*

Figure 2

Prospective Analysis Method for Emerging Technologies

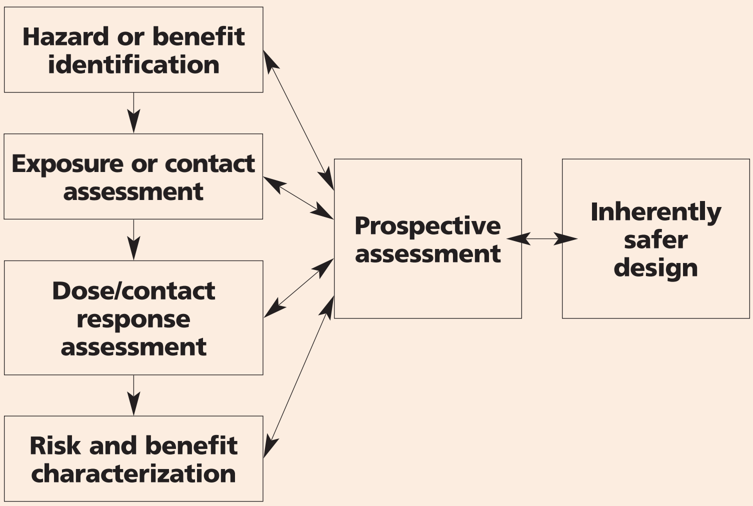


Table 1

Elements of Prospective Analysis

Element	Description (based on current and accrued information)
Hazard or benefit identification	Qualitatively describe emerging technologies, the potential applications of these technologies, the full range of information available about one or more of these applications, and the implications of that information for occupational health.
Exposure or contact assessment	Evaluate the probability of workers' exposure to or contact with an identified new technology.
Dose/contact response assessment	Quantitatively determine the nature and magnitude of the adverse or beneficial effects to worker safety and health that would be potentially associated with exposure to or contact with an emerging technology.
Risk and benefit characterization	Separate significant risks or benefits from those that are trivial, address uncertainties, and identify principle knowledge gaps.
Prospective assessment	Extrapolate beyond what is known about an emerging technology and attempt to forecast future risks and benefits.
Inherently safer design	Avoid and not just control occupational hazards.

Note. *NIOSH, 2005a.*

ipate benefits and risks in the initial stages of a technology's design, development and use is complex. Two identification searches are needed. The first type seeks technologies that can improve occupational safety and health, either directly or through enabling research. The second and more difficult type of search seeks to identify problems in new workplace processes, equipment, materials and work practices before they enter the workplace in order to direct their development toward safer and healthier results. System safety analysis techniques can help identify these problems (Clemens & Pfitzer, 2006).

An example of both hazard and benefit identification is the light-emitting diode (LED) technology, which has the potential to move from a niche market of LED screens and other low-light intensity applications to replacing the $40 billion incandescent and fluorescent lighting industry. The switch to an LED illumination economy could cut electricity consumption by 10% worldwide, save $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 designs for reflecting devices. However, there may be a more benign technology, organic light-emitting diode, which could be produced by a process such as 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 risks may vary with different technology options.

A current application of LED technology that demonstrates its benefit cost analysis is an effort to replace incandescent lamps in traffic signals in Portland, OR. In 2001, the municipality replaced 6,900 red, 6,400 green and 140 flashing amber incandescent lamps with LED lamps. The annual savings was $335,000 energy and $45,000 on maintenance. The initial net cost was $900,000, which was spread over several years through a lease agreement, and the leaser received a $500,000 tax credit for the investment. The LED lamps must be replaced every 6 years as compared to incandescent lamps, which must be replaced every 2 years.

In a parallel activity, the hazard of LED use for viewing, as in traffic lights, had been overestimated (Horak, 1999). As a result, a risk assessment of LEDs was conducted to modify the safety standards for visible LEDs well after their initial development rather than during their development, and this was when the costs of complying with an unnecessarily high standard were recognized.

Exposure & Contact Assessment

Converse to NRC's sequence of steps in the risk assessment process, we place exposure before dose/response assessment since—in a causal chain—exposure to a hazard precedes the resulting dose or contact with the body. NRC (1993) has defined exposure assessment as "the process of measuring or estimating the intensity, frequency and duration of human exposures to an agent currently present in the environment or existing hypothetical exposures that might arise from the release of new chemicals into the environment" (p. 249). Exposure and contact assessment associates the amount of contact with aspects of the technology. The word "contact" is added to emphasize exposure to energy and resulting injury (NRC, 1993). This element consists of using current information to evaluate the probability of workers' exposure to or contact with a new technology. Apart from information on the agents themselves (i.e., source, distribution, concentrations and characteristics), knowledge gaps exist on the probability of the population's exposure to the hazard. The result of this element is to estimate the probable increase or decrease in exposure or contact associated with an emerging technology. Moreover, this estimate takes into account the routes of exposure (e.g., dermal, respiratory).

An example of an exposure assessment of an emerging technology relates to metallic aerosols, gaseous emissions and noise from a robotic-assisted metal spray process. The process was designed to provide a quality and uniform deposition of metallic particles on engine block cylinder walls, but the potential inhalation hazard of this process to workers was unknown. While exposures did not pose a problem at the research and development stage, the investigators recommended due diligence, as the technology was deployed to prevent exposures that cause a health risk including hard metal lung disease (Chan, Rouhana & Mulawa et al. 1995).

Dose/Contact Response Assessment

NRC (1993) has defined dose-response assessment as "the process of characterizing the relation between the dose of an agent administered or received and the incidence of an adverse health effect . . . as a function of the human exposure to the agent" (p. 249). Dose/contact response assessment 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 an emerging technology. The result of this element is to quantify the health outcomes associated with either a risky or beneficial emerging technology (NIOSH, 2005a).

As an example, nanotechnology has emerged as a key strategic branch of science and engineering in the 21st century. The interagency working group 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." Nanotechnology 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. Much work is underway to associate nanoparticles with human health effects. However, to be meaningful, this work must be predicated with exposure information, which is currently lacking.

Risk & Benefit Characterization

NRC (1993) defined risk assessment as "the process of estimating the incidence of a health effect under the various conditions . . . combining the exposure and dose/response assessments," which is the least developed step of risk assessment (p. 253). Risk characterization is used to separate significant risks from those that are trivial and to address uncertainties. Risk and benefit characterization separates significant from trivial risks and benefits through quantitative characterization, where possible, and the application of expert judgment. The risks and benefits of an emerging technology are synthesized in this element from the preceding elements, which corresponds to estimation based on its uncertainties, probability, frequency and severity of potential adverse effects. When the available data are inadequate or inconclusive, a cautious approach to safety and health would be to opt for the worst case (NIOSH, 2005a).

An example of risk and benefit characterization is the nuclear pebble bed reactor, an emerging technology being seriously pursued in China (Reiss, 2004). This technology is an advanced nuclear reactor design for producing electricity and indirectly cracking water to produce hydrogen. The design has the significant benefit of eliminating a potential meltdown, which is possible in light water reactors. It can be more easily constructed from modules, is less complex than water reactors and eliminates the potential for steam explosions. Nonetheless, it still produces nuclear waste, uses flammable graphite, and has been known to release radiation into the environment when a pebble (golf-ball-sized sphere used as fuel) jammed and damaged the feed pipe wall.

Prospective Assessment

Prospective assessment extrapolates what is known about a new technology and attempts to forecast future risks and benefits. It represents an attempt to go beyond current information and data to answer "what if" and "how could" questions (Ayres, 1969), and uses forecasting techniques such as scenario analysis (Ayres; Schoemaker & Mavaddat, 2000). It is an attempt to identify and prevent future problems in workplaces. This fifth element is embedded in the other four elements of the prospective analysis, but as a separate element, prospective thought is emphasized.

An example of prospective assessment is the evaluation of potential health hazards from exposure to an aerosol from a non-CFC mobile air conditioner system [Chan, Rouhana et al., 1995). "What-if" scenarios simulated worst-case exposures to various workers. Mechanics were found to be at low risk, whereas in albeit unlikely system ruptures, drivers could be exposed to high concentrations for brief periods.

Application of the prospective analysis framework should be conducted by risk/benefit analysts in an iterative fashion as a new technology progresses through its development. New information, such as toxicological data on materials used in the manufacture of the technology would inform the iterative process and trigger an updated prospective analysis. Furthermore, this element would be informed by a companion element inherently safer design.

Table 2

Principles of Inherently Safer Designs

Principle	Description	Example
Intensification or minimization	Use minimal amounts of hazardous materials.	Storing smaller quantities of a chemical reduces releases so they are not catastrophic.
Substitution	Use safer materials or processes.	The Phosphorous Match Act of 1912 led to the elimination of white phosphorous in manufacturing matches by substitution.[a]
Alternative reaction routes	Use the same raw materials in a different order to eliminate a toxic intermediate product.	A different reaction route eliminated methyl isocynate as an intermediate product from the production of the insecticide, Carbaryl.
Modification or attenuation	Change the unit operations so as to reduce hazards such as high pressure or temperature.	Storing ammonia or chlorine at a pressure below their boiling point results in an evaporation rate that is relatively low in case of a leak.
Energy limitation	Reduce the amount of energy available in the production process.	Eiffel assembled parts of his tower in Paris on the ground to avoid exposure to falls from a high elevation on the tower.[b]
Simplification	Eliminate unnecessary complexity and be tolerant of operators' errors.	The nuclear power plant incident at Three-Mile Island was related to a complex technology.[c]
Optimal plant layout[d]	Modify logistics to avoid risks.	Separate pedestrian and vehicular traffic.
Exact manufacturing[e]	Design the process so that all inputs are consumed in production with no waste.	Use the precision of nanotechnology to eliminate waste products.

Note. *[a]Myers & McGlothlin, 1996 pp. 330-2, [b]Barry, 1972 p. 50, [c]Perrow, 1999 p. 61, [d]Zwetsloot & Ashford, 2003 p. 219, [e]Hood, 2004, p. A745.*

Inherently Safer Design

The best way to prevent a risk is to eliminate the hazard, which is the highest priority of the safety hierarchy (Manuele, 2005). Worker safety and health may be improved by replacing hazardous technologies with emerging technologies that are benign, by implementing alternatives that are less hazardous or by providing technologies that augment good health.

Inherent safety is an intrinsic feature of the design (Krigman, 1985), and by intervening at the design stage of emerging technologies, inherently safer designs can be applied at minimal cost prior to capital investment and may lead to cost savings (Mannan, 2002). As applied to chemical processes, inherently safer design involves several methods (also called principles) as shown in Table 2 (Hendershot, 1999; Mannan, 2002).

An example of inherently safer design is illustrated by the simplification of the production process for the chemical synthesis of DNA, which is an emerging technology for the pharmaceutical industry. Two principles of inherent safety—simplification and substitution—were applied to reduce the hazard and the cost of bringing this technology to market. The production process was redesigned to use fewer solvents and reagents by halving the number of steps from four to two. Moreover, the use of the most highly toxic reagents and solvents were designed for elimination to reduce chemical waste by 75%. Not only could safety be improved, but the expense of hazardous solvent and reagent waste disposal could also be reduced—a cost equivalent to the purchase of the chemicals (Sprackland, 2002).

Principles for inherently safer design are needed for emerging technologies especially beyond the chemical manufacturing industry. These approaches must be explored in other sectors such as agriculture, construction, transportation, healthcare and services (NIOSH, 2005a). One model to examine is TRIZ (an acronym of the Russian, meaning theory of inventive problem solving), which is based on 40 design principles to avoid the evolution of a technology by trial-and-error. It purports to control the future by defining inherent contradictions in the design (e.g., hazard versus benefit) and systematically applying design principles to transform the contradictions into solutions that eliminate the hazard while maintaining or augmenting the benefit (Altshuller, 2000; Rantanen & Domb, 2002).

Future Directions

In advancing occupational safety and health throughout the emerging technology development process, teamwork and continuous iterations within the team are necessary as new facts emerge. An SH&E professional should be part of each emerging technologies development team. It includes the traditional risk assessment steps of hazard identification, exposure assessment, dose/contact assessment, and risk characterization, but it adds an element of prospective assessment that asks the "what if" and "how could" questions (Ayres, 1969). To eliminate or reduce the hazards, inherently safer designs must be applied to emerging technologies in a broad range of industrial sectors. Principles of inherently safer designs may lead to the application of emerging technologies to eliminate or reduce existing pernicious occupational injuries and illnesses.

The emerging technologies team supported a nanotechnology symposium in the U.K. in October 2004 (Mark, 2004), and a symposium in Minneapolis, MN, on "Nanotechnology and Occupational Health," in October 2005 (NIOSH, 2005b). These symposia addressed the potential hazards related to applications of nanotechnology as an emerging technology. This is an area that bears watching as applications of prospective analysis are used (NIOSH, 2005a). In addition, the following should be pursued:

- The prospective analysis model must be validated and improved through application.

•The applications of spiral development as a risk assessment tool in information technologies that are used to eliminate software flaws must be monitored as a metaphor for eliminating or reducing occupational hazards (Liu, In & Jung, 2001).

•The TRIZ processes must be analyzed for additional principles for inherently safer designs especially for applications beyond the chemical manufacturing industry.

•Communications to inform emerging technology teams of the latest facts must be facilitated to avoid delays of the peer-reviewed literature, perhaps following the weekly report model of the Mortality and Morbidity Weekly Report, which is published by CDC (www.cdc.gov/mmwr).

•The approach should be holistic, addressing environmental and consumer hazards and benefits as well as those related to work.

Conclusion

As NIOSH implements its second round of NORA, a shift is being made from 21 to 8 industrial sectors (www.cdc.gov/niosh/NORA/intro.html). Table 3 shows the mapping of the eight sectors plus the energy sector against several identified emerging technologies that could have implications for worker safety and health. The prospective assessment and inherently safer designs methods can be adopted as part of the occupational safety and research agendas for each of these industrial sectors.

SH&E professionals can apply the prospective assessment techniques described in this article during the development of new technologies by adding relevant cost and benefit considerations, iterative processes that bring new information to the table continually and by asking "what if" questions. MacCollum (2002) describes the application of inherently safer design principles for improving construction safety. Within his hazard identification/prevention matrix, priority must be placed on the elimination of the hazard as established in the hierarchy of controls. His examples of hazard elimination bear repetition herein, for they can be applied through emerging technology life cycle analyses, which includes facility construction.

•Develop safer designs (e.g., wet rather than dry paint removal).

•Apply safety appliances on equipment (e.g., remote sensing devices).

•Substitute safer machines or materials (e.g., instant table saw blade stoppage technology).

•Relocate dangerous facilities (e.g., bury powerlines to eliminate potential overhead electrical contact).

Table 3

New & Emerging Technologies by Industrial Category

New and emerging technologies	NORA 2 category								
	Agriculture, forestry, fishing	Construction	Healthcare, social assistance	Manufacturing	Mining	Services	Transportation, warehousing, utilities	Wholesale, retail trade	Energy
Fuel/propulsion technology[ac]					X		X		X
Global positioning systems[abcd]	X	X			X		X		
Intelligent transportation systems[a]							X		
Genetically modified organisms[ab]	X								
Antibiotics[a]	X		X						
Medical automation[a]			X						
Biosensing devices[ab]	X		X						
Medical imaging[a]			X						
Alternative energy sources[a]							X		X
Aeronautic robotics[a]	X	X			X		X		
Space exploration[a]		X	X						
Security technology[a]				X				X	
Biometrics[a]			X						
Nanotechnology[a]	X	X	X	X	X	X	X	X	X
Information technology[a]					X	X	X	X	
Automatic steering, auto pilot and computer-operated processing equipment[b]	X	X			X				
High-pressure hydraulic systems[bc]	X				X				
High-speed equipment[b]	X								
Irradiation of food[b]	X		X						
Land application of sludge[b]	X						X		
Operatorless/remote control tractors and machinery[b]	X	X			X				
Power transmission lines and communication towers[b]	X	X							X
Inertial navigation systems[d]		X							
Active beacon systems[d]		X							
Ground-based radio frequency systems[d]		X		X					
Ultrasonic and optical systems[d]		X							
Radio frequency identification systems[d]	X	X	X	X					
Smart structures[d]		X			X				
Modular construction and advanced materials[d]		X							
4-D visualization[d]		X			X				
Total electronic integration[d]		X		X	X				
Leaching processes[c]					X				
Sensor technology[c]				X	X				
Communication and data networks[c]				X	X				
Equipment monitoring and diagnostics[c]	X	X			X		X		
Maintenance-free systems[c]	X	X			X		X		

Note. *New and emerging technologies (not mutually exclusive) by industrial category. Relevant cells have been marked beyond those cited in the source documents. [a]All sectors (Breysse & Herbstman, 2005, pp. 1-12), [b]Agriculture (U.S. Dept of Agriculture, 2003, p. 6), [c]Mining (Peterson et al., pp. 28-60), [d]Transportation construction (Griffin et al., 2003, p. 2-6) .*

•Develop criteria for safe assembly of structural components at the construction site (e.g., remotely controlled connectors for elevated steel assembly). ■

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