SUMMARY

Over the past century, technology advances have had major impacts on mining practices and the nature of the mine and quarry sites in the United States. The evolution of current technologies, as well as the introduction of innovations, will continue and perhaps accelerate in the new century. Several industry objectives will drive future technology change, including

- Lowering production costs.
- Enhancing the productivity of workers and equipment.
- Opening up new reserves and extending the life of existing ore bodies.
- Continuing to meet regulatory and stakeholder requirements in areas such as health and safety, environmental impacts, and land use.

Between March and July 2000, the RAND Science and Technology Policy Institute conducted a series of in-depth, confidential discussions with key members of the mining community to elicit a wide range of views on technology trends in all sectors of the U.S. mining and quarrying industry. The discussions included 58 organizations engaged in coal, metals, aggregates, and industrial minerals production, as well as technology providers and research institutions.

This report brings to light those technologies viewed by industry leaders as critical to the success of the industry currently, and critical technologies likely to be implemented between now and 2020.

THE MINING INDUSTRY

During the discussions, several important trends impacting the mining industry in the United States were highlighted. These include historically low commodity prices, consolidation and globalization, and regulatory and political constraints on new development. According to industry managers, these trends have resulted in a mining community that is risk-averse and struggling against thin profit margins; in addition, the community has severely cut back on technology research and development (R&D). This has led to a situation in which technology investments tend to focus on short-term and incremental refinements rather than long-term or breakthrough innovations.

Given the higher unit prices of the goods they produce, metals producers tend to be investing more heavily in complex and advanced technologies such as dispatch systems, high-precision equipment positioning, and super-size machinery. In the future, metals producers are likely to spearhead the implementation of remote-controlled and automated equipment. Coal producers, on the other hand, presented themselves as less concerned about mine-productivity-enhancing technologies, primarily because of chronic oversupplies on coal markets and regulatory pressures on coal utilization.

The stone and aggregates industry is in a much different position: Quarries have been operating at record levels of output and enjoying strong revenue streams since the early 1990s as a result of the prolonged U.S. economic expansion and generous public-sector infrastructure spending. Given the aggregates industry's financial prospects, as well as its rapid consolidation and less-advanced technology baseline (in comparison with the rest of the mining industry), we conclude that quarries in the United States may see the fastest pace of technological change in the industry in the coming decades. As rising buyers of new machinery and equipment, stone and aggregates producers also stand to become important drivers of mining technology innovation.

THE CRITICAL TECHNOLOGIES

When asked to identify the technologies critical to resolving the major mine-productivity bottlenecks, industry representatives with whom we spoke identified a fairly consistent set of priority areas:

1. Information and communications technologies for process optimization.
2. Remote control and automation.
3. Operations and maintenance.
4. Unit-operations capabilities.

These four priority technology areas are summarized below.

Information and Communications Technologies

Our discussions of critical technologies indicated that the information revolution is coming to the mining industry and will have a significant impact on mine operations in the coming years. Information technologies (IT) were cited frequently as one of the most important advances shaping mining and quarrying practices, since they enable both management and staff to monitor, evaluate, and adjust operations in real time to maximize productivity and minimize cost.

Mining equipment is increasingly being outfitted with sensors and information-processing capabilities to control and manage operations. As such advanced equipment becomes more widespread, more operations at the mine site can be tied together by communications and data networks, enabling minewide process integration and control capabilities. Ultimately, these networks can supply data to a central control or to off-site providers who can then "layer-in" a range of services and support functions, such as mine planning and equipment-maintenance solutions.

According to mining executives, the IT revolution is beginning to have a significant impact at mine sites. They cited several examples:

- Planning and visualization technologies permit mines to accurately simulate different choices of initial mine design, operations, equipment types, expansion options, closure outcomes, and the ways these factors influence each other.
- Dispatch systems using the Global Positioning System (GPS) monitor equipment positions, direct materials flows, and optimize capacity utilization in real time.
- GPS-based surveying can now be integrated with high-precision drilling and earthmoving, so mine maps and plans can be updated in real time as materials are moved.
- The availability of sitewide information-sharing has provided the capability to begin integrating previously separate operations, such as surveying, mining, processing, and reclamation.

While mine operations are generating more data, many discussants noted that the information is rarely well utilized at the present. Accordingly, another critical technology is effective knowledge management: tools and capabilities for distilling complex mine information into an actionable format that can be comprehended and acted upon in real time.

Remote Control and Automation

Remote control and automation have been high on the mining R&D agenda for a long time; however, there is a lack of consensus within the mining community regarding the desire for, expectations of, and impacts from the deployment of remote-controlled and autonomous equipment. There was no consensus

Table S.1

Anticipated Availability of Autonomous Mining Equipment

Equipment	Anticipated Date
Autopositioning shovel bucket	2001
Autonomous surface-haul truck	2002–2005
Autonomous LHD vehicle	2005
Autonomous surface drill	2003
Autonomous shovel	2005

Source: RAND discussion participants.

among the RAND discussion participants on the feasibility or benefits of remote and autonomous equipment operation, and the discussants also differed in their views on where these technologies would be commercialized most rapidly.

Remote and autonomous control technologies are still in the formative stages and are currently available in only a few specific tasks, such as remote guidance of load-haul-dump (LHD) vehicles and continuous miners, operator-assisted drill positioning, excavator scooping, and vehicle tramming. Despite this climate of uncertainty, study participants expressed the opinion that the requisite technologies are nearing commercial availability for several pieces of machinery (see Table S.1).

Operations and Maintenance

Given the large expenditures on capital equipment characteristic of mining, technology developers and users alike place a very high priority on improving equipment performance and availability through better operations and maintenance practices and technologies. This coincides with assessments of critical technologies across U.S. industry.

Improving equipment operations and maintenance (O&M) has gained greater importance as margins have been squeezed by competition and weak commodity prices, as mining equipment and geological conditions have become more complex, and as mine processes are becoming more tightly integrated.

Several priority O&M concepts currently are being developed and applied in mining, with the central goals of better understanding maintenance requirements, optimizing the use of maintenance resources, and boosting equipment availability:

- Mining equipment is being outfitted with an increasing variety of on-board sensors for monitoring critical systems. Together with enhanced off-board diagnostics, such as vibration analysis, vital-signs monitoring helps operators predict equipment failures and schedule maintenance actions.

- Mining operations are investing in better maintenance areas, greater contamination control, more thorough and effective record-keeping, and more complete and careful work.
- More robust engineering and materials, such as improved lubricants and maintenance-free systems, together with improved service access and "hot-swappable" components, are extending operational capabilities and reducing downtimes.
- Maintenance outsourcing is becoming increasingly prevalent in mining, mirroring a widespread trend in business. Arrangements include shipping equipment to maintenance and repair specialists off-site, transmitting equipment diagnostic data directly to service contractors and parts suppliers, and having contract maintenance personnel and equipment on-site.

Understanding and optimizing equipment operations and availability were cited by several industry leaders as critical prerequisites for the successful implementation of remote and autonomous operations.

Unit-Operations Capabilities

Central to the mining process, unit-operations (unit-ops) machinery and equipment are by definition critical technologies. However, industry representatives noted that despite their importance to the mining process, existing unit-ops equipment technologies are unlikely to change substantially in the next two decades, and with few exceptions, those technologies in use today at mine sites in the United States will still be in use in 2020.

Technology changes that are being implemented are incremental and typically focus on increasing batch size, reducing cycle intervals, and boosting equipment availability. The expected commercial introductions of several unit-ops technologies are summarized in Table S.2.

Table S.2

Anticipated Availability of Selected Unit-Ops Innovations

Technology	Anticipated Date
Solid-state programmable blast detonators	2000
Six-unit miner-bolters	2000
Mechanical cutter for hard-rock applications	2003
Fuel-cell-powered underground equipment	2010
1000-ton-capacity haul truck	2020
150-cubic-yard-capacity shovel	2020

Source: RAND discussion participants.

Many discussants predicted and welcomed the continuation of the trend toward higher-capacity haul trucks, shovels, loaders, and excavators. Some executives, however, questioned whether the size of haul trucks and excavators has reached a feasibility threshold where the economies of scale have peaked.

HUMAN FACTORS

The term *technology* includes not only physical hardware, but also operational procedures, organizational structures, and management practices. The inclusive nature of this definition is important: According to the industry leaders with whom we spoke, some of the most important innovations concern the organization and management of mining and quarrying facilities. To this point, a critical component in the technology equation raised repeatedly in the discussions was human factors.

One major issue on which human factors entered into the technology discussion is health and safety. Interestingly, all things considered, complying with health and safety regulations *was not* cited as a driver of technological change. Rather, industry leaders typically pointed to what they saw as innovative personal safety equipment or programs their firms had undertaken on a voluntary basis that went beyond regulatory requirements. Many innovations cited in the discussions specifically address the perceived need to create a more enjoyable, interesting, and productive work environment in order to attract and retain the best workers in a very competitive hiring environment.

Indeed, the discussion participants suggested that as technology progresses, workers are becoming *more critical* to the success of mining and quarrying operations, not less:

- As mining equipment increases in scale and staffing levels decline, individual operators play a greater role in determining mine output.
- As mining equipment becomes more advanced through IT and communications innovations, line workers are gaining unprecedented access to information and control over the equipment they are operating.
- Achieving the productivity gains sought by both management and investors requires that miners develop new, multidisciplinary skills to fully utilize emerging technologies, and that their roles be upgraded from following rules to solving problems.

At the same time, many participants explicitly downplayed the importance of hardware innovations in determining performance outcomes. Rather, they emphasized the importance of engaging and motivating their workforces. Even when a new technology may be seen as potentially beneficial, building workers' acceptance of the technology and their commitment to using it to its greatest extent is an essential prerequisite to successful implementation.

IMPLICATIONS

Several implications can be drawn from the discussions on technology trends and public- and private-sector involvement in technology research, development, and diffusion in the future.

Discussants from all corners of the mining community agreed that both the amount of activity and the level of cooperation on mining technology R&D efforts in the United States had decreased substantially over the past few decades. Yet discussion participants repeatedly raised the concern that more R&D overall *and* more R&D collaboration among technology suppliers and between technology suppliers and operating companies were required. The need for collaboration is clear: The demand for mining equipment and services is limited, advanced technologies are increasingly complex, and R&D needs are often too great for a single company to support. In short, R&D roles as well as funding levels need to be reappraised in the industry to meet the technology objectives viewed as important by the industry itself. Funding for R&D partnerships provided by the Department of Energy (DOE) Office of Industrial Technologies and supported by the National Mining Association was mentioned as a positive step in this direction—suggesting that the federal government has an important role to play in convening parties and catalyzing ventures.

When asked to highlight critical technologies, operating company participants often focused first on downstream technologies (e.g., for refining) rather than upstream activities such as blasting. This tendency reflects several factors, including the fact that productivity gains tend to increase as value is added to a product while it moves downstream. However, as processing plants become more highly tuned and as the just-in-time delivery principle becomes more important, the quality and stock of feed materials become more important determinants of plant performance. This suggests that R&D and innovations targeted at upstream mining processes are likely to have higher payoffs in the future and thus merit closer attention.

Mining in the United States has a tradition of self-reliance: Mines typically are in remote locations, and the ore bodies they work often have unique characteristics. The discussion participants suggested that existing information transfer and technology search mechanisms in the industry also do not appear to be fully exploiting opportunities for technology crossover within companies, across the mining industry, or, importantly, with nonmining sectors. Previous RAND research has indicated that maintenance is a critical-technology concern for many industries. Diagnostics such as vibration, lubricants, and ultrasonic analysis are now common in industries with relatively small capital investments in their fleets. Over-the-road trucking, construction, and manufacturing—like mining—have high downtime costs, and the mining companies could gain tremendous benefit from learning about new maintenance concepts and best practices in these sectors. The mining industry can also draw on the expertise of the U.S. Department of Defense (DoD), for example, in managing complex maintenance and repair operations and in the advanced use of modular designs, subsystem replacement, and centralized repair depots. Other technology crossover areas of opportunity identified include Total Quality Management (TQM), "Six Sigma" enterprise process redesign, and pollution prevention.

We encountered widely differing views on the prospects for many new technologies, for example, super-size haul trucks and automation. These differences of opinion were rooted in varying assessments of the expected performance, costs, and benefits of new technologies. At the same time, it was repeatedly noted that operating companies—especially smaller ones—have limited knowledge of costs across their operations. This may be skewing priorities in favor of conventional technologies and practices and slowing the development and diffusion of important new technologies. Measuring economic productivity benefits of new technologies—especially IT—is a notoriously difficult task for any industry. Moreover, mining and quarrying operations today also compete on a range of other parameters that are difficult to measure: the ability to attract skilled and motivated workers; health and safety, environmental, and aesthetic impacts; customer satisfaction; and community acceptance. Objective, third-party measurement and assessment of emerging technologies on productivity and other important measures could better support the positive impacts of critical-technology acquisition, as well as R&D investment decisions.