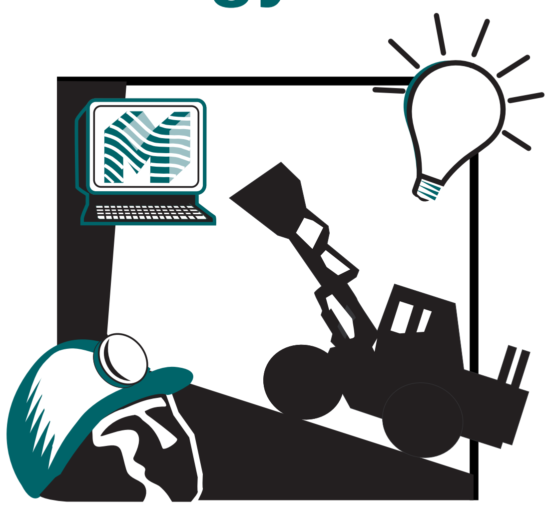
Mining
Industry of the Future

Exploration and Mining Technology Roadmap



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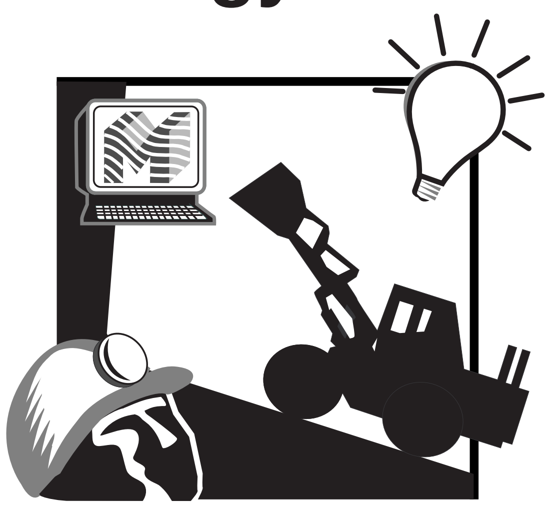

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Foreword

In June 1998, the National Mining Association and the U.S. Department of Energy entered into a compact to pursue a collaborative research partnership, the Mining Industry of the Future. Following the creation of this partnership, the mining industry developed *The Future Begins with Mining: A Vision of the Mining Industry of the Future*. That document, completed in September 1998, describes a positive and productive long-term vision for the U.S. mining industry. It also establishes long-term goals for the industry.

Using the Vision as guidance, the Mining Industry of the Future is developing technology roadmaps to guide collaborative research activities. This *Exploration and Mining Technology Roadmap* represents the third roadmap for the Mining Industry of the Future. It is based upon the results of the *Exploration and Mining Roadmap Workshop* held May 10 ñ 11, 2001. The workshop was sponsored by the National Mining Association and the U.S. Department of Energy.

Workshop participants represented a wide range of mining industry sectors and interests. These individuals came from mining companies, equipment suppliers, government agencies, research laboratories, and universities. Participants included:

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Introduction

Mining plays a vital role in our national economy, national security, and in the life of each individual. Each year, nearly 47,000 pounds of materials must be mined for each person in the United States to maintain their standard of living. Processed materials of mining origin account for nearly five percent of U.S. gross domestic product.[1] U.S. electricity costs are among the lowest in the world due to the availability of low-cost coal. In fact, coal accounts for 51 percent of all electric power generated in the United States.[2] In 2000, the value of shipments of mined materials processed domestically was $429 billion.[3] More than 276,000 people work directly in the U.S. mining industry.[4] Indirect employment in manufacturing, engineering, environment, geology, and others accounts for nearly three million additional jobs.

An efficient and productive mining industry requires constant progress in the processes and technologies used in exploration and mining. While the mining industry uses many of the latest technologies to locate and mine materials, further process and technological advances are needed to enable enhanced and more efficient resource identification, characterization, and production. These advances in exploration and mining will contribute to accomplishing the 2020 goals set forth by the Mining Industry of the Future in *The Future Begins with Mining: A Vision of the Mining Industry of the Future*. These goals are:

- ***Responsible Emission and By-Product Management-*** Minimize the impact from mining activities on the environment and the community by fully integrating environmental goals into production plans. Support the development of technologies to reduce carbon dioxide emissions to near zero and sequester additional emissions.

- ***Safe and Efficient Extraction and Processing-*** Use advanced technologies and training to improve the worker environment and reduce worker exposure to hazards that reduce lost-time accidents and occupational diseases to near zero.

- ***Superior Exploration and Resource Characterization-*** Develop ways to find and define larger high-grade reserves with minimal environmental disturbance.

- ***Low-Cost and Efficient Production-*** Use advanced technologies to improve process efficiencies from exploration to final product.

- ***Advanced Products-*** Maintain and create new markets for mining products by producing clean, recyclable, if possible, and efficiently transportable products, and form cooperative alliances with the processing and manufacturing industries to jointly develop higher-quality and more environmentally friendly products.

- ***Positive Partnership with Government-*** Work with government to reduce the resource development cycle time by two-thirds. Achieve equitable treatment for mining, relative to international competition, compared to other industries that produce materials and energy by making the legal and regulatory framework rational and consistent.

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[1] Estimates developed by National Mining Association based on data from US Department of the Interior, US Geological Survey, *Mineral Commodity Summary* (mineral consumption); US Department of Energy, Energy Information Administration, *Monthly Energy Review* (coal energy consumption); US Department of Commerce, Bureau of Census (population), <http://www.nma.org/fastfacts.html#anchor208017>.

[2] *Mining Engineering*, Annual Review, May 2001.

[3] *Mining Engineering*, Annual Review, May 2001, 33.

[4] Mine Safety and Health Administration, *Worktime Quarterly Reports*, (2001 data is preliminary), updated: April 2002.

- ***Improved Communication and Education-*** Attract the best and the brightest by making careers in the mining industry attractive and promising. Educate the public about successes in the mining industry of the 21st century and remind them that everything begins with mining.

To achieve these vision goals, the mining industry has developed roadmaps to direct research and development. The first of these roadmaps, the *Mining Industry Roadmap for Crosscutting Technologies,* was published in February 1999 and focuses on technologies that could impact the processes for all products of the mining industry. The second roadmap, the *Mineral Processing Technology Roadmap*, was developed in September 2000 and addresses those technologies that will improve energy efficiency and productivity in multiple process areas.

This document, the *Exploration and Mining Technology Roadmap*, focuses on process and technological advances that will improve the exploration for, and extraction of, ore from the earth. Exploration includes locating economic deposits and establishing their nature, shape, and grade. Activities involved in exploration include geological surveys, geophysical prospecting (both ground and aerial), boreholes and trail pits, surface/underground headings, drifts, or tunnels. Mining, as used here, is the extraction or removal of ore from surface or underground mines. This involves excavating activities such as digging, blasting, breaking, loading, and hauling. There are significant opportunities for improving energy efficiency and productivity in these and other areas. This roadmap describes pathways for process and technology research identified by industry to advance exploration and mining and to help industry achieve its vision goals. Research needs are categorized under three broad categories:

1. Exploration and Mine Planning
2. Underground Mining
3. Surface Mining

The remainder of this document describes research needs identified by industry in each of these categories. It provides roadmaps outlining exploration and mining improvements with specific interim and long-term targets (See pages 22-24).

Exploration and Mine Planning

Exploration and mine planning activities include prospecting, sampling, mapping, exploratory drilling such as rotary and percussive drilling, and other work involved in searching for ore.

Prospecting begins with field geology and geologic mapping. The prospector looks for trace amounts of ore minerals, favorable rock types, and alterations that may have been caused by mineralization solutions. Useful techniques at the reconnaissance stage include remote sensing and the use of photographic and radar images taken by satellites or aircraft. If conditions warrant, samples of the mineral deposit are sent for chemical analysis, called an assay.

It is generally believed that tomorrowís mineral discoveries in established mining areas will likely come from depths greater than known ore bodies. These discoveries might also come from areas covered by thick layers of overburden. Finding these deposits requires more sophisticated technology than traditional prospecting methods. For example, buried targets can be explored by diamond drilling. Knowing where to aim the drill entails the use of one of two key methods of geological-surveys, geophysics, or geochemistry.[5]

A geological survey is a systematic investigation of an area determining the distribution, structure, composition, history, and interrelations of rock units. Its purpose may be either purely scientific or economic with special attention to the distribution, reserves, and potential recovery of mineral resources.

Geophysical exploration is used to determine the nature of earth materials by measuring the physical property of the rocks and interpreting the results in terms of geologic features or the economic deposits sought. Physical measurements may be taken on the surface, in boreholes, or from airborne or satellite platforms.

Geochemical exploration is the search for economic mineral deposits by detection of abnormal concentrations of elements in surficial materials or organisms, usually accomplished by instrumental, spot-test, or quick techniques that may be applied in the field. Examples of these exploration methods include:

- **Magnetic methods -** A geophysical prospecting method that maps variations in the magnetic field of the Earth that is attributable to changes in structure or magnetic susceptibility in certain near-surface rocks. Most magnetic prospecting is now done with airborne instruments.
- **Resistivity -** Any electrical exploration method in which current is introduced into the ground by two contract electrodes and potential differences are measured between two or more other electrodes.
- **Induced polarization -** The production of a double layer of charge at a mineral interface or production of changes in double-layer density of charge, brought about by application of an electric or magnetic field.
- **Spontaneous polarization -** Electrochemical reactions of certain ore bodies causing spontaneous electrical potentials.
- **Electromagnetic methods -** Group of electrical exploration methods through which one determines the magnetic field that is associated with the electrical current through the ground.
- **Gravity method -** Mapping the force of gravity at different locations with a gravimeter to determine differences in specific gravity of rock masses and, through this, the distribution of masses of different specific gravity.

[5] The Northern Miner, *Mining Explained* , Ontario Canada, 1998

- **Seismic methods -** Exploration techniques utilizing the variation in the rate of propagation of shock waves in layered media.

- **Radiometric methods -** The use of portable Geiger-Muller apparatus for field detection of emissions count in search for radioactive minerals.

RESEARCH NEEDS

Research activities to improve productivity and efficiency in exploration and mine planning are grouped into two categories: resource characterization and mine planning. Within resource characterization, there are several research needs in both underground and surface geochemical and geophysical areas. Exhibit 1 shows the R&D needs listed in the *Mining Industry Roadmap for Crosscutting Technologies*. In addition to the description below, research needs and targets are illustrated in the research pathways in Exhibit 4 (page 22).

Exhibit 1.
Crosscutting Technologies Roadmap R&D Needs in Exploration and Resource Characterization

Remote Sensing Technology

- Develop real-time mineral content sensors for all minerals
- Conduct research and development to improve the accuracy of deep (>1000' beneath the surface) sensing of rocks, minerals, elements, and structures
- Develop horizon sensing and interface detection on exposed material
- Develop projectiles that can be shot into the ground and can transmit geological information
- Develop ways to sense and interpolate non-intrusive geological modeling of underground ore bodies
- Develop a better understanding of the physics of remote technology
- Conduct research to predict the process response of ore via remote sensing characterization of that ore
- Develop better laser analytical technologies and use improved modeling to increase sensor accuracy
- Develop new sensors operating from space, high altitudes, low altitudes, above ground, and below ground
- Develop rugged hand held laser technologies for on-the-spot chemical analysis
- Develop sensors for effective underwater exploration
- Develop sensors that can relate geological information

Imaging Technology

- Develop ways to sense, visualize, interpolate, model, and predict geological anomalies in front of mining equipment
- Develop superconducting quantum interference devices (SQUIDs) for imaging
- Combine methane draining and imaging
- Develop more analytical tools to facilitate accurate interpretation
- Develop cross-well instrumentation
- Develop geophysical resolution modeling to enable enhanced mine modeling and mine planning software
- Develop borehole radar for measurement while drilling

Navigation and Controls

- Develop sensors for guidance and navigation of semi-autonomous machines
- Develop non-geodetic referenced positioning technology
- Develop remote control and autonomous exploration device for extreme environments

Resource Characterization

The ability to define, with a high degree of confidence, the location and quality of mineral resources can dramatically improve the economics and energy efficiency of mining. Research is needed to develop a better understanding of the economic viability and environmental impacts associated with extraction prior to physical exploration and mining. The primary goal of characterization research is to enable the industry to conduct resource characterization activities faster, better, cheaper, and with less impact to the environment. Characterization research addresses nearly each vision goal.

Surface Material Characterization ñ Much research is needed in geochemical and geophysical exploration techniques to improve surface material characterization. Improved modeling for both 2-D and 3-D technologies can improve geological, geochemical, and geophysical characterization. Also, there are opportunities to reduce the need for additional resource characterization with better satellite imaging and instant scanning of the mine surface in open pit mining. An increase in basic research can result in benefits to industry. For example, better understanding in areas such as soil and rock characteristics can help to determine where ore deposits may be located. Research to reduce the environmental impact and reduce human exposure to the environment can be accomplished with the use of low-cost autonomous equipment. In addition, non-invasive mineral characterization can also reduce the environmental impact of exploration. Technologies in imaging and sensors can be used to replace certain tasks such as drilling to characterize an area without disturbing the environment.

Underground Material Characterization - Research is needed to improve small-scale technologies for underground material characterization. This includes reducing machine size and developing nano-scale tools. Smaller exploration technologies can help in characterizing reserves that are difficult to reach. In addition, underground Ground Positioning Systems (GPS) are needed to enable better subsurface material characterization. Improved methods are needed for directional drilling to tap new resources. Directional drilling is a method of drilling involving the use of stabilizers and wedges to direct the orientation of the hole.[6] In addition, sensing technologies are needed to automatically guide the drill so that it remains in the ore during drilling. Among the issues that will need to be resolved by this research are adverse impacts caused by downhole shock and vibration.

Research also is needed on larger-scale, crosscutting subsurface characterization technologies to improve material analysis. An example is re-enhanced electromagnetic imaging. Electromagnetic (EM) methods are a group of electrical exploration methods through which one determines the magnetic field that is associated with the electrical current through the ground. The EM method detects conductive ore bodies, not mineralization. Traditional EM methods had little ability to ìseeî more than about 100 meters below the surface. New, low-frequency EM methods, ìpulseî techniques and magnetotelluric methods that use the Earthís own EM field have increased the depth penetration of EM prospecting. Because EM surveys do not require electrical contact with the ground, they are among the most useful techniques in airborne geophysics. Low-frequency, EM methods allow detection of a presence of conductive sulphide mineralization (typically the host rock for Ni, Cu, Pd, and Pt) within 300 meters of the probe. Lowering the probe into a drill hole can, in effect, survey the surrounding rock for conductive deposits in a diameter of up to 600 meters.[7] Down-hole surveys are used at more advanced stages of exploration, where some drilling has already been done.[8]

[6] The Northern Miner, *Minning Explained* , Ontario Canada, 1998.
[7] LK&Z Advisory International Inc. ìSmall Capî Letter. *Starfield Resources Inc. SRU:CDNX. <http://www.starfieldres.com/>*.
[8] The Northern Miner, *Minning Explained* , Ontario Canda, 1998.

Geophysics is used to determine the nature of earth materials by measuring the physical property of the rocks and interpreting the results in terms of geologic features or the economic deposits sought. There is a need to improve geophysical analysis for cross-borehole correlation such as EM methods. Specifically, research is necessary on low-cost, shallow seismic characterization. Seismic prospecting is a geophysical method of prospecting, utilizing knowledge of the speed of reflected sound waves in rock.[9] There is a need to develop techniques for performance of shallow seismic reflection surveys, which would produce images of subsurface structure in the depth range of 2 to 100 meters.

There are additional research needs in the areas of subsurface material characterization. For example, improved characterization of deposits with see-through strata technologies can reduce costs associated with exploration at deep depths. Also, improving forward modeling and inversion algorithms can play an important role in geophysical exploration and environmental site characterization. Another area for research is developing alternative approaches to drilling to minimize the environmental impact and violent nature of the tool-rock interface, specifically non-invasive mineral characterization through *in-situ* real time geochemical analysis and models with improved technologies for geological, geochemical, and geophysical modeling.

Crosscutting Characterization- There are also a number of research needs that relate to both underground and surface material characterization. Research on ore deposit formation with improved thermodynamic and kinetic studies to characterize deposits can benefit both underground and surface characterization. Target modeling can also crosscut these areas through exploration models that show ìwhat to look forî in environmentally sensitive ore deposits. Also, a database on exploration results is needed for future reference to avoid further expense.

Industry estimates the potential benefits of improved characterization to be:

- Twenty-five percent reduction in the cost per unit of resource discovered.
- Twenty-five percent increase in identified resources from current government baseline estimates.
- Twenty-five percent increase in exploration activity as measured by the number of active claims on federal lands.
- Fifteen percent reduction in energy used per unit of resource discovered.
- Ten percent reduction in area of land disturbed per unit of resource discovered.
- Elimination of fatalities and lost-time accidents.
- Increased confidence in reserve base.

Mine Planning

The mining industry seeks to consistently develop mine plans that have a low degree of risk, result in reduced environmental impacts, and can be readily approved by regulatory entities. Ultimately, the industry would like to further integrate exploration and mine site planning. This will require an increased knowledge base as well as development of new mine planning tools and techniques.

One area for research in mine planning is modeling. Better geohydraulic models are needed not only for mine planning but also for exploration purposes. Also, 3-D models are needed with high data density and higher confidence levels. Models need to be in real-time and help provide access to material volume that will increase initial ore hits. Models are also needed to better measure environmental impacts of mining to help prevent environmental issues before they occur. These models need to be user-friendly to help in geophysical and geochemical data interpretation.

[9] Ibid.

Mine planning research also needs to include other areas such as technologies for re-mining. Re-mining are the techniques used and exploitation of minerals from previously mined deposits. Re-mining will reduce the amount of new mines needed. In addition, mine planning should incorporate technologies to identify properties of ore in real-time to allow for tagging and tracking the ore.

In addition, research is needed to improve the ability to further incorporate industrial ecology, including integrating innovative methods for reclamation into mine planning and modeling practices. The aim of industrial ecology is to interpret and adapt an understanding of the natural system and apply it to the design of the man-made system. This helps achieve a pattern of industrialization that is not only more efficient but is intrinsically adjusted to the tolerances and characteristics of the natural system. The emphasis is on forms of technology that work with natural systems, not against them.[10]

Research in improved mine planning techniques addresses nearly all mining vision goals. In addition, it will produce several important benefits, including:

- Higher confidence in reserve base.
- Increased resource identification.
- Five to thirty percent reduction in cost, depending on mineral commodity, per unit of resource produced.
- Five to thirty percent energy savings, depending on mineral commodity, per unit of resource produced.
- Reduced permitting time to less than two years from the initial application date
- Elimination of deaths and lost-time accidents.
- Minimized environmental disturbances up to ten percent as measured by land disturbance per unit of resource produced.
- Higher recovery rates, thereby reducing costs and energy consumption.

[10] Hardin B. C. Tibbs, *Industrial Ecology: An Environmental Agenda for Industry*, 1992, Department of Energy, Center of Excellence for Sustainable Development.

Underground Mining

Underground mining is used to reach ore bodies that have been identified deep beneath the surface of the Earth. To get to the ore body, a vertical shaft, horizontal adit, or inclined passageway must be developed. This allows for the removal of ore and waste and provides ventilation. The ore is then mined by conventional methods, continuous mining or in the case of some coal mines, longwall mining.

Once the ore body is exposed, several levels of horizontal tunnels called drifts and crosscuts are created. They provide access to mining areas called stopes. The area actually being mined at any given time is called the face. Mined material is hauled from the face by conveyors, trains, loaders, or trucks that go directly to the surface or to the shaft, where it is hoisted to the surface, and sent to a processing facility.

RESEARCH NEEDS

Exhibit 2 lists the R&D needs from the *Mining Industry Roadmap for Crosscutting Technologies* for safe and efficient mining that apply to both surface and underground mining. Specifically, there are a variety of challenges in underground mining where technology and process research will significantly improve energy efficiency, productivity, and performance in underground mining. These activities are grouped into four categories:

- Near-Face Operations
- Ancillary Operations
- Maintenance Operations
- Technical Services

In addition, there is a crosscutting need for better training of miners for the future. This will require advanced simulation tools for education and judgment training. Also, research is needed to improve the man-machine interface and to reduce ergonomic risks to workers.

Near-Face Operations

Near-face operations are those that take place at the site where the ore is actually being mined. A top research priority is to develop and apply intelligent and/or remote-controlled robotic technologies to reduce worker exposure to hazards, while improving mining productivity.

With many of the large, easily accessible ore bodies extracted, systems for dealing with difficult and smaller ore bodies are needed. A *high-priority* research need for the industry is the miniaturization of mining machines to increase the amount of difficult-to-reach ore that can be extracted and the development of selective mining techniques for extracting only high-quality ore. Also, there is a need to improve real-time analysis during drilling to ensure directional control and accuracy. For example, research is needed on ìimaging ahead of mining.î This process involves sensors to monitor and detect geologic conditions in front of the mining machine and allows for corrections to avoid mining unwanted materials. Imaging ahead of mining will reduce waste material that must be transported, crushed, processed, and disposed, which saves large amounts of energy, reduces environmental impacts, and improves the final product.

Solution mining can be less energy intensive and less environmentally intrusive. To increase the applicability of solution mining, improvements are needed in areas such as preconditioning, which is used to treat the ore before extraction. Research is also needed in the area of solution mining for metals. This includes innovations to improve and create permeability in the ore body to enhance *in-situ* mining.

Improvements and innovations are needed in material haulage. Haulage is the use of vehicles or other equipment to draw, convey, or move workers, supplies, ore, and waste underground. For the purposes of this roadmap, it also includes alternatives to blasting. Blasting is a hazardous method of removing rock and is unpredictable in the manner in which it fragments the rock.

Improvements or alternatives to blasting will improve worker safety by increasing the knowledge of blasting effects or by removing the danger. Improvements will also increase efficiency in materials haulage by allowing more control over the size and amount of material blasted. Research on high-pressure water innovations for advanced extraction can be one alternative to blasting. Improvements in blasting can also contribute to reducing waste material that must be transported, crushed, processed, and disposed, saving large amounts of energy, reducing environmental impacts, and improving the final product.

Improvements in re-mining techniques are also needed to extract ore that has been left in the mine to provide support without compromising the structural integrity of the mine. Improvements in areas such as solution mining and material removal can assist in addressing these issues.

Ancillary Operations

Ancillary operations are those that support the overall mining activities but do not directly involve mining the ore. There are many research needs in underground ancillary operations including the need for increased automation. Automation, a *high-priority* research need, can improve production and efficiency and reduce worker exposure. Other research areas for increasing safety and health include the reduction of noise exposure to workers and ground control systems such as roof bolting systems. An alternative to roof bolting is strata control research, which will improve mine safety while reducing the need for roof bolting activities. Improvements in these areas can reduce ancillary energy use.

Better underground ventilation and dust control is needed to improve health conditions and to reduce costs and energy use. Research priorities include the need to recover valuable methane from mines and to develop methods to safely control the emissions before they are emitted into the atmosphere.

Improvements in underground processing to reduce the need to manage above-ground waste can also reduce energy consumption in downstream processing. For example, better cutting and ore fragmentation can reduce the need for crushing. Research in alternative power sources for mining vehicles, such as fuel cells, is needed to further reduce or eliminate exhaust emissions and increase fuel efficiency. Research is also needed for new haulage systems that are more efficient and productive. One area for new haulage systems is hydraulic pneumatic vertical transportation systems. Research must also focus on improving systems for back stowage of tailings.

Maintenance Operations and Material Wear

Maintenance operations are those needed to maintain the equipment used for near-face and ancillary operations. Research is needed to improve material-wear characteristics for equipment such as drills. The development of smart materials and components and underground machine diagnostics can provide equipment operators with valuable information regarding maintenance needs and failures. Underground machine diagnostics were identified by industry as a *high-priority* research need. Machine diagnostics are used to maintain and service the equipment used in the mines. There are examples of military machine diagnostic technologies that could be applied to mining equipment with some adjustment. Also, research in robotic repair and maintenance can reduce labor costs and worker exposure to hazardous conditions at the mine face. This research can result in zero unscheduled downtime for equipment.

Exhibit 2.
Crosscutting Technologies Roadmap R&D Needs for Safe & Efficient Mining

Mining Equipment
- Develop method for high-pressure water extraction
- Improve prognostic capability of equipment
- Research and catalog material wear properties
- Develop equipment to traverse steeper slopes
- Develop autonomous mining equipment
- Develop more efficient, alternative power supplies for equipment
- Improve robotics for underground operations
- Develop “miniature” technologies for mining thin seams or small veins
- Develop new mobile equipment fuels and fuel strategies

Mining Process
- Develop communications system for surface-underground and surface-surface communication
- Improve roof control to handle difficult mining conditions
- Understand and control solution migration underground
- Develop blasting techniques that minimize noise, dust, and flying rock
- Reprocess mine waste to recover saleable by-products
- Better understand processes that lead to emissions
- Transfer oil recovery techniques to *in-situ* mining
- Reliably model and predict impacts of emissions
- Develop more efficient *in-situ* extraction and near-face beneficiation
- Develop alternatives for material transportation

Sensors
- Develop ways to monitor entire mining environment (workers, equipment, communication, systems)
- Develop rugged sensors that can work in small, hot environments
- Develop geological sensing devices to monitor and evaluate material ahead of the working face

Mine Planning
- Develop method for using bore drilling information to predict what lies ahead
- Adapt what has been developed for other industries to mining
- Develop system to integrate geologic data into models
- Develop a better understanding of rock mechanics

Health & Safety
- Develop comfortable, integrated, cost-effective safety equipment to protect respiration, ears, and eyes
- Develop advanced simulation / virtual reality systems
- Develop ergonomic robotics
- Develop warning systems for catastrophic failures
- Develop lighter weight materials and supplies for worker safety

Technical Services

Technical services allow mines to operate more efficiently and include communications, software, and other service items. The development of underground positioning systems and underground monitoring of mining vehicles to improve efficiency and remote operation is needed. Research is also needed in underground communication and data transfer systems. This will improve energy efficiency and safety in mining. Both underground positioning systems and communications have been identified as *high-priority* research needs. In addition, research is needed on crosscutting applications software for data mining. This should include software that tracks past and current research results, which is an important tool in directing mining research. Other research needs include:

- Non-invasive and deeper *in-situ* analysis of ore body technologies.
- Integrated holistic real-time modeling systems.
- Tag and track systems for large volumes of materials.

Meeting research needs in the areas of near-face and ancillary operations, maintenance and material wear, and technical services will contribute to the long-term goal of increasing productivity and efficiency in addition to reducing costs by at least 75 percent.

Surface Mining

Surface mining is mining at or near the surface. It is generally done where the overburden can be removed without too much expense. It is the primary method of extracting coal, metal ore, and industrial minerals in the United States. In 1998, 65 percent of coal, 97 percent of crude metal ore, and 97 percent of industrial minerals produced in the United States came from surface mines.[11]

Surface mines for metallic minerals are traditionally conical in shape and feature a series of benches winding down into the pit to extract materials from near-surface ore bodies. The benches are used as working areas and haul roads. The rock is drilled, blasted, and loaded into large haul trucks that take it to a processing facility, which is generally at or near the mine. Surface mines for industrial minerals are generally in layers from 4 to 25 feet thick and do not require drilling and blasting. Industrial minerals are generally removed with shovels, draglines, and loaders.

RESEARCH NEEDS

There are significant opportunities to make advances in methods of extracting, fragmenting, and hauling/ handling mined material in surface mines. Research in these areas will improve productivity and energy efficiency, while reducing the environmental impact of mining. In addition, there are crosscutting needs related to improving worker safety and training as well as improving planning and integration. Industry has identified seven categories of research needs in surface mining:

- Solution Mining
- Materials Handling
- Equipment
- Human Factors
- Fragmentation
- Systems Integration
- Automation and Robotics

Solution Mining

Solution mining for surface mining will reduce the amount of material that must be extracted. Revolutionary advances are needed to increase the viability, cost effectiveness, and application of solution mining. In addition, reducing the cost of bio/bacterial extraction methods is a *high-priority* research need in solution mining. Also, research is needed on innovative processes and technologies that can create and/or improve permeability for *in-situ* mining. Innovations in solution mining techniques are needed to make it available to more commodities including copper and gold. In the long-term, research is needed to enable cost-effective offshore or seabed mining.

Research advances in solution mining will result in both energy and safety improvements by reducing excavation and land disturbance requirements. Moreover, they will result in significant reductions in dust emissions and worker exposure and improvements in production efficiencies.

Materials Handling

There are numerous improvements that could be made to materials handling efficiency. Ultimately, this research should help the industry to achieve truly continuous or near-continuous mining. Currently, the use of lightweight materials in the manufacture of trucks used at the both

[11] US Department of Energy, Energy Information Administration, *Coal Industry Annual 2000.*
US Department of the Interior, U.S. Geological Survey, *Mining and Quarrying Trends, 2000.*

the mine site and for delivery is a *high-priority* need for the industry. Lightweight, high-strength materials being developed in the automotive sector should be adapted for use in mining.

In addition to material reduction that will result from enhanced exploration and mining techniques, there are other opportunities to reduce the amount of material handled. Lean manufacturing concepts and models that will reduce material handling requirements should be investigated and applied to mining. Lean manufacturing allows companies to utilize all available resources in the most efficient manner. Also, technologies and methods such as blasting techniques or alternatives to blasting to achieve appropriate sizing of materials handled should be developed and tested. This is a *high-priority* for the industry.

Design and development of new and innovative haulage systems is also *high-priority* research need. Advanced technologies that utilize oxy-diesel (ethanol) using fuel injection without the loss of power can be deployed. In addition, research on hydraulic/pneumatic transportation systems and technologies is necessary.

Achieving these improvements in materials handling technologies and systems has the potential to improve productivity by as much as 20 to 30 percent over the near-term. Over the long-term, these developments could significantly reduce mine-site emissions, including dust emissions, by 50 percent. Realizing continuous or near-continuous mining could improve efficiency by 50 to 70 percent over the long-term.

Equipment

Research to develop smart systems and advanced materials for mining will improve productivity, safety, and energy efficiency in surface mining. Currently, research is needed to develop prognostics for predictive maintenance. Technologies to make mining equipment self-analyzing, capable of identifying problems before they occur, and self-repairing will allow problems to be resolved prior to breakdown. *High-priority* research also will focus on developing smart, durable, and wear-resistant materials and components for mining equipment. Many of these research needs also apply to underground mining (see **Underground Mining** section).

Equipment research should also focus on developing new battery technologies for use in mining equipment and on creating new and innovative alternatives to powering mining equipment. Related to this, industry has identified the need for advanced, high-performance in-mine transport systems to replace trucks. This may include conveyors able to maneuver steep inclines and sharp corners. Technologies and processes for ìre-miningî also are needed.

Research to enable predictive maintenance could lead to reductions in fleet operation and maintenance costs by 15-20 percent over the near-term. Combined with improvements in wear materials and other equipment advances, life cycles could be extended by as much as 100 to 200 percent.

Human Factors

Human factors play an enormous role in mine safety and productivity. There are many opportunities to use new technologies and workplace concepts to improve workforce capabilities. Simultaneously, there is a clear and recognized need to capture the institutional memory and expertise of the industryís most veteran workers.

Advanced simulation tools are a *high-priority* research need for worker training, as are new technologies for distance learning. Existing simulation techniques developed for laboratory or military applications should be investigated for potential applications in mining. These systems should attempt to capture the knowledge and judgment of mining experts. Similarly, educational systems should be developed to improve training.

Existing ergonomic and safety concepts can be applied to reduce the risk associated with the man-machine interface. Monitors can be designed and installed to observe the alertness of machine operators, thereby improving worker safety. There is a near-term need to improve planning on health and safety procedures and training for new chemicals being introduced in the industry. Incremental implementation of new technologies, such as robotics, can begin in the near-term, leading to advanced application of these technologies over the long-term. Research in these areas can help to achieve significant reductions in injuries and fatalities as well as contribute to surface mining efficiency by as much as 15 to 20 percent.

Fragmentation†

New techniques for fragmentation have the potential to elicit important efficiency and environmental improvements in mining. For example, controlled blasting is a *high-priority* research need. Controlled blasting should result in a smaller footprint and less shock, vibration, and noise for the surrounding area. Ultimately, research should lead to alternatives to blasting as a method for fragmentation. This was identified as a *high priority* by the industry. This research will be particularly applicable to quarries and other surface mining operations in urban and suburban areas. Innovations in the use of high-pressure water technologies should also be investigated as an alternative fragmentation technology, where appropriate.

Research that leads to the design, development, and deployment of advanced fragmentation technologies has significant potential to reduce the surface mining footprint and dust emissions over the near-term, while improving the public perception of the industry and improving fragmentation efficiency.

Systems Integration

The surface mining industry should further employ and improve an integrated systems approach to surface mining operations. This approach incorporates all aspects of surface mine siting, preparation, excavation, production, environmental management, delivery, material and water reuse, and remediation in the up-front planning process. It also includes integrating innovative methods for reclamation. The objective is to optimize the economics of mining. Logistics and planning schemes currently used for military operations can be further investigated and adapted for mining operations.

A model cooperative process that focuses on systems integration should be developed. It could, for example, include a cooperative process between industry, government, and other interested parties to reduce permitting time. Permitting time is often a hindrance to rapid implementation of new technologies or methodologies that can help facilitate a systems approach.

Ultimately, systems integration should lead to a lean manufacturing system, inventory management from mine face to point-of-sale, low waste, and truly continuous mining. Major research is needed over the near- to long-term to achieve an integrated mining system. Such a system incorporates up-front planning features such as:

- Methods to measure the environmental impacts of mining.
- Prevention and treatment of contaminants through new techniques such as in-phyto remediation.
- Improvements in bio/bacterial remediation.
- Ground control/slope stability.
- Dry process systems/technologies from extraction to beneficiation, thereby reducing water use.

Systems integration also incorporates sustainable development concepts, making efficient use of information technologies, characterization technologies, selective mining technologies, raw materials, process activities at or near the mining face, and all materials with market value to be extracted, processed, and sold. It also includes reusing process residues, identifying new and useful applications of current waste materials and lands, suppressing dust emissions, reducing the cost of wastewater remediation, and investment in remediation.

Automation and Robotics

Automation and robotics technologies present enormous opportunities for mining operations. Research is needed to design these technologies for a range of applications in mining. Examples include:

ï Tagging and tracking systems for real-time identification of materials in batching *(high-priority).*
ï Automated communication and data transfer systems (*high-priority*).
ï Sensors to read material properties and adjust ongoing treatment for continuous process control (*high-priority*).
ï See-through strata technologies (*high-priority*).
ï Repair and maintenance using robotics.
ï Utilizing radio frequency (RF) tags to assist in asset management.
ï Improved global positioning systems and applications.
ï Autonomous imaging, sensing, and blasting technologies.
ï Laser technologies to perform *in-situ* analysis of ore bodies.
ï Miniaturized extraction technologies.
ï Automated slurry wall technology (a new system or special slurry) to eliminate open-pit mining.

Additional Challenges

A number of challenges must be overcome to realize the research benefits identified in this roadmap. These challenges directly and indirectly affect exploration and mining improvements and will be integral to any advances the mining industry makes in achieving the vision goals. They include:

ï **Environmental Management -** The mining industry needs to continue to manage and prevent environmental problems before they occur. In addition, the industry must anticipate emerging regulatory issues.

ï **Federal Lands -** Much of the higher-quality ore is found on federal lands. Further cooperation between government and industry is needed to develop mutually beneficial methods of mining on federal lands.

ï **Interagency Coordination -** Federal agencies need to better coordinate R&D activities and share R&D results with the mining industry. This is particularly important on R&D that is too high risk for industry to perform alone. One example of a high-risk effort is basic science research related to mineral exploration and mining, such as geology or rock mechanics. Also ìblue skyî technologies are high-risk but may have large benefits. For example, the U.S. military has logistic planning schemes and equipment that, with minor adjustments, could benefit the mining industry.

ï **Data Collection -** There is a lack of reliable information on exploration results, equipment data, R&D results and other important information. This data could be a valuable tool in decision-making with regard to where to explore, where to mine, what equipment to use under certain circumstances, and what research has already been conducted to avoid duplication.

ï **Permitting and Regulation -** Issues regarding permitting and regulations need to be resolved. Efforts expediting the certification process can help the mining industry to meet the needs of the nation.

ï **International Technology Transfer -** Internationally, a better technology transfer system is needed between mining companies so that the most efficient and widely accepted technologies and processes are being used. Mining is largely an international industry and more efficient and environmentally sound technologies may be in use in other countries that can benefit the U.S. mining industry.

ï **Public Perception -** Public perception is a large challenge for the industry, and the critical role of the mining industry to our economy and quality of life is often overlooked. Publicizing the development and use of exploration and mining improvements through this roadmap is needed to show that the mining industry is not only a cleaner, safer, and more technologically advanced industry than is commonly perceived, but that the industry is vital to meeting the needs of the population.

ï **Sustainable Development -** Sustainable development will be based on the development of technological advances. These advances will make efficient use of information technologies, characterization technologies, selective mining technologies, raw materials, process activities at or near the mining face, and all materials with market value to be extracted, processed, and sold. It also includes reusing process residues, identifying new and useful applications of current waste materials and lands, suppressing dust emissions, reducing the cost of wastewater remediation, and investment in remediation.

- **Basic Science -** The U.S. mining industry cannot afford to conduct basic scientific research that could help better understand exploration and mining. Improved coordination with government is needed to perform collaborative basic research and to transfer the results of other federally funded R&D that may be applicable to the mining industry.

Achieving Our Goals

The successful implementation of research activities charted in the *Exploration and Mining Roadmap* will contribute greatly to achieving the vision goals. Again, those goals are:

- ***Responsible Emission and By-product Management-*** Minimize the impact from mining activities on the environment and the community by fully integrating environmental goals into production plans. Support the development of technologies to reduce carbon dioxide emissions to near zero and sequester additional emissions.

- ***Safe and Efficient Extraction and Processing-*** Use advanced technologies and training to improve the worker environment and reduce worker exposure to hazards that reduces lost-time accidents and occupational diseases to near zero.

- ***Superior Exploration and Resource Characterization-*** Develop ways to find and define larger high-grade reserves with minimal environmental disturbance.

- ***Low-Cost and Efficient Production-*** Use advanced technologies to improve process efficiencies from exploration to final product.

- ***Advanced Products-*** Maintain and create new markets for mining products by producing clean, recyclable, and efficiently transportable products and form cooperative alliances with the processing and manufacturing industries to jointly develop higher-quality and more environmentally friendly products.

- ***Positive Partnership with Government-*** Work with government to reduce the time for resource development cycle by two-thirds. Achieve equitable treatment for mining relative to international competition compared to other industries that produce materials and energy by making the legal and regulatory framework rational and consistent.

- ***Improved Communication and Education-*** Attract the best and the brightest by making careers in the mining industry attractive and promising. Educate the public about the successes in the mining industry of the 21st century and remind them that everything begins with mining.

Each area identified in this roadmap contributes to these goals as illustrated in Exhibit 3.

Exhibit 3. Achieving Vision Goals

Vision Goal	Research	Impact
Responsible Emission and By-Product Management	- Alternatives to, and control of, blasting - Industrial ecology of mining - Improvements in underground processing - Alternative power/fuel sources - Improved systems for back stowage of tailings - Recover valuable methane from mine ventilation - Environmental baseline to include natural background	- Decrease mining footprint 30% - Reduce dust emissions 100% - Improve equipment life cycle 100-200% - Reduce air emissions 70-80% - Reduce environmental disturbance 10%, as measured by land disturbance per unit of resource produced
Safe and Efficient Extraction and Processing	- ***Innovative haulage systems*** - ***Automation and Robotics*** - Reduce materials handling - High-pressure water technologies - Prognostics for predictive maintenance - Smart, durable, wear-resistant materials - Worker training and safety - Selective mining techniques - Alternatives to blasting - Ground/strata control systems	- Decrease hazardous exposure 80% - Zero fatalities - Efficiency improved through continuous mining
Superior Exploration and Resource Characterization	- Modeling tools - Automation and robotics - Reduce materials handling - High-pressure water technologies - Prognostics for predictive maintenance - Smart, durable, and wear-resistant materials - Worker training and safety - Selective mining techniques - Alternatives to blasting - Ground/strata control systems	- Improve recovery 10% - Increase reserve/recovery base - Increase exploration activity 25% measured by the number of active claims on federal land - Reduce energy consumption per unit of resource discovered 15% - Increase identified resources 25% - Minimize environmental disturbance 10%, measured by land disturbance per unit of resource discovered

High-priority research items are shown in ***bold-italics***.

Vision Goal	Research	Impact
Low Cost and Efficient Production	- ***Improvements in-solution and in-situ mining*** - ***Lightweight materials with better wear characteristics*** - ***Smart materials, components, and underground machine diagnostics*** - ***Underground positioning, monitoring, and communication systems*** - Cost-effective offshore or seabed mining - Truly continuous or near-continuous mining - Technologies and processes for ìre-miningî - New battery technologies for use in mining equipment - Systems for dealing with difficult and smaller ore bodies - New haulage systems - Developments in real-time drilling - Imaging ahead of mining - Integrated holistic real-time modeling systems - Tag and track systems of mined materials - Crosscutting applications software for data mining - Lean manufacturing principles	- Improve fragmentation efficiency - Reduce Labor costs 50% - Environmental disturbance by 10%, measured by land disturbance per unit of resource produced - Increase productivity and efficiency and reduce costs by at least 75% - Improve unscheduled downtime for equipment to zero - Reduced energy use 5 to 30% per unit of resource produced - Improve price through consistency of product 7 to 15%
Positive Partnership with Government	- Models for cooperative process for permitting - Improved mine planning technologies	- Create cooperative process for permitting that includes industry, government, and the environmental community - Cut permitting time to less than two years from the initial application date - Improve public perception
Improved Communication and Education	- ***Simulation and training for workers*** - Facilitated educational systems	- Provide sustainable, skilled workforce - Improve worker safety

High-priority research items are shown in ***bold-italics***.

Exhibit 4. Roadmap for Exploration and Mine Planning

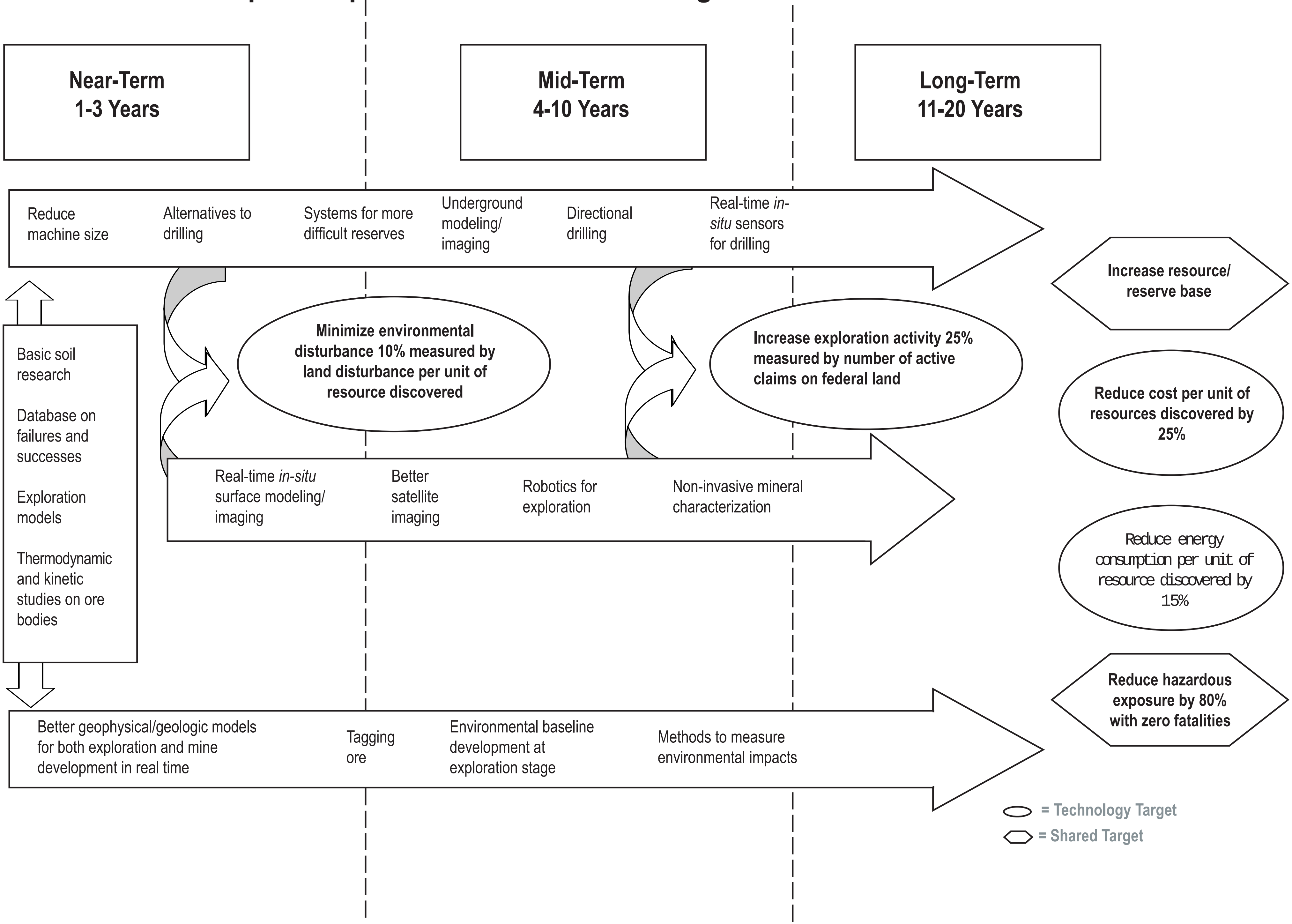

Exhibit 5. Roadmap for Underground Mining

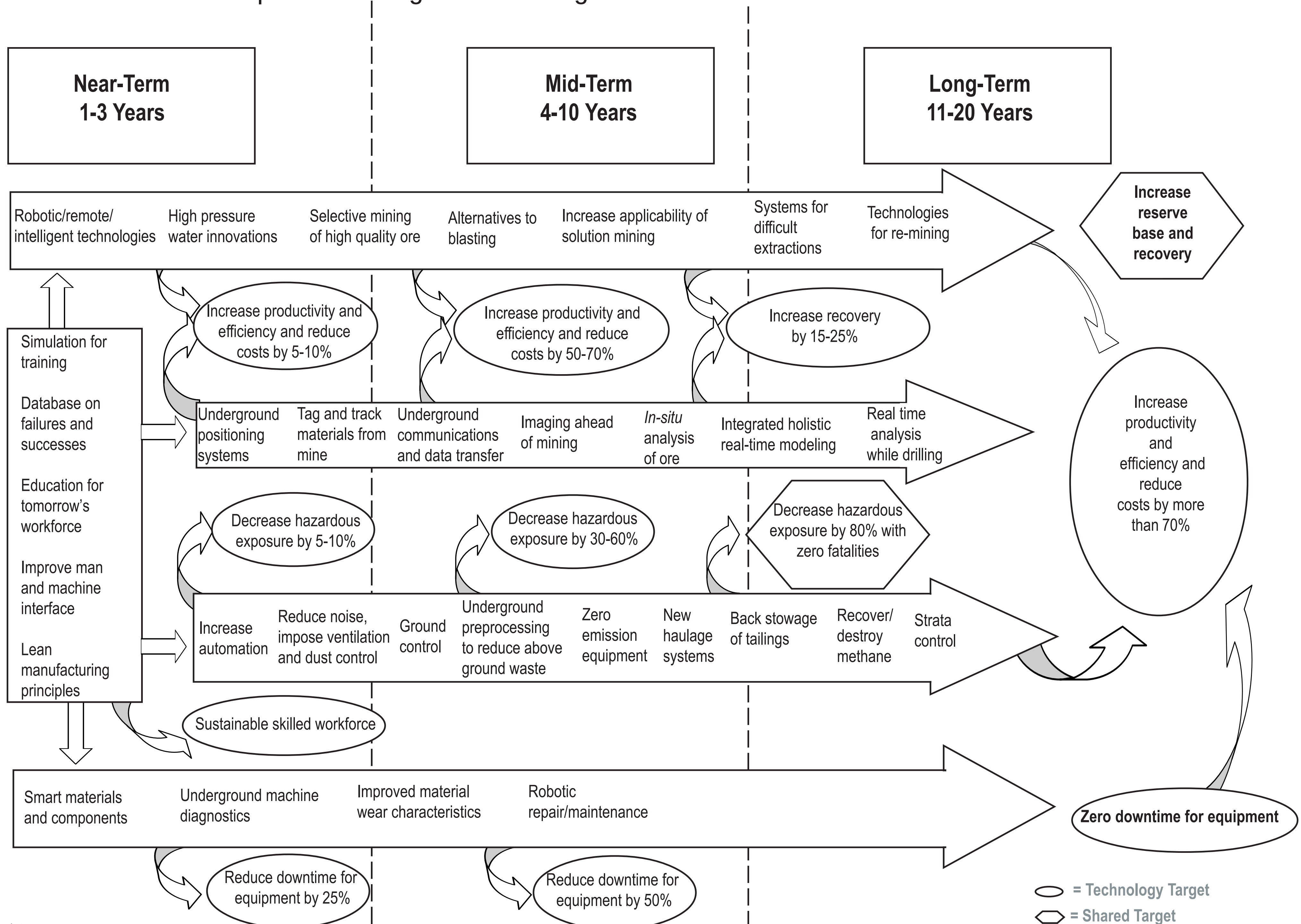

Exhibit 6. Roadmap for Surface Mining