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Development of a Mine Rescue Drilling System (MRDS)

Phase I Report

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Abstract

Sandia National Laboratories (Sandia) has a long history in developing compact, mobile, very high-speed drilling systems and this technology could be applied to increasing the rate at which boreholes are drilled during a mine accident response. The present study reviews current technical approaches, primarily based on technology developed under other programs, analyzes mine rescue specific requirements to develop a conceptual mine rescue drilling approach, and finally, proposes development of a phased mine rescue drilling system (MRDS) that accomplishes (1) development of rapid drilling MRDS equipment; (2) structuring improved web communication through the Mine Safety & Health Administration (MSHA) web site; (3) development of an improved protocol for employment of existing drilling technology in emergencies; (4) deployment of advanced technologies to complement mine rescue drilling operations during emergency events; and (5) preliminary discussion of potential future technology development of specialized MRDS equipment. This phased approach allows for rapid fielding of a basic system for improved rescue drilling, with the ability to improve the system over time at a reasonable cost.

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Executive Summary

The safety of people involved in underground coal mining is of great priority to all involved, from miners and operators to regulators and rescuers. Therefore, a technology that significantly reduces the time required to locate and potentially rescue miners trapped in underground accidents is of importance to a wide range of interests. Sandia National Laboratories (Sandia) has a long history in developing compact, mobile, very high-speed drilling systems, and this technology could be applied to increasing the rate at which boreholes are drilled during a mine accident response. The present study reviews current technical approaches, primarily based on technology developed under other programs, analyzes specific requirements of mine rescue to develop a conceptual mine rescue drilling approach, and finally, proposes development of a phased mine rescue drilling system (MRDS) that accomplishes (1) development of rapid drilling MRDS equipment, (2) structuring improved web communication through the Mine Safety & Health Administration (MSHA) web site, (3) development of an improved protocol for employment of existing drilling technology in emergencies, (4) deployment of advanced technologies to complement mine rescue drilling operations during emergency events, and (5) preliminary discussion of potential future technology development of specialized MRDS equipment. This phased approach allows for rapid fielding of a basic system for improved rescue drilling, with the ability to improve the system over time at a reasonable cost.

The major conclusions and recommendations of this study are as follows:

- Locating miners underground occurs through various means, but probe boreholes remain a key method and can lessen the use of underground rescue teams.

- A specialized bottom hole assembly (BHA) is the proposed first-step MRDS engineered element because it is compact (quick deployment), works with moderately modified standard equipment, and is not expensive to maintain.

- To be of value, MRDS technology must improve drilling rates significantly in sedimentary geologic sections that may be saturated. Preliminary tests have demonstrated rapid penetration of sedimentary rocks for short distances. A field-scale demonstration still needs to be conducted.

- MRDS development can proceed in phases beyond the proposed BHA as a result of continued study to encompass improved practices with existing equipment and systems and discussions of potential improvements in made-for-purpose equipment.

- The specialized MRDS BHAs should be stored in strategic locations around the country at locations with easy access to air transport for rapid deployment to event sites.

- Any MRDS operation will have to mitigate potential explosive conditions related to drilling in a disrupted mine environment.

- The evolving MRDS will always operate within the MSHA emergency management framework.

- The MSHA emergency framework could be augmented with web features that better enable MRDS deployment and use.
- In terms of the development of an MRDS, we recommend the following path forward:
  - Develop an advanced BHA for mine rescue drilling technology based upon high-performance percussive hammer technology.
  - Current compression equipment is bulky and difficult to transport. It is used however for remote drilling operations and can likewise be transported for a mine rescue drilling situation. Small, air-transportable compression equipment could be developed to support the power requirements of the MRDS.
  - Development of a compact nitrogen production unit for the MRDS should be considered to ensure explosive hazard mitigation when drilling into disrupted mine conditions with explosive potential
  - An alternative to nitrogen units would be the development of an explosive atmosphere mitigation foam compatible with the hammer drill and suitable for breathable atmospheres.

1 Introduction

This report will present the results of a set of design development studies conducted by Sandia National Laboratories (Sandia). This work includes background studies that led to our current understanding of the existing drilling technology and its limitations; a detailed study of drilling technology components and their applicability to a mine rescue drilling system (MRDS); a set of trade-offs between technologies of potential use for MRDS; a review of mine accident histories that illustrate real-world challenges to MRDS; the development of a preliminary concept of operations for MRDS; a concept for using the Mine Safety & Health Administration (MSHA) web site for improved communications relevant to emergency drilling response; and the definition of a path forward for designing and field testing the drilling component of the MRDS. Note that all acronyms are defined in Appendix A and the definition of the work scope under which this effort was undertaken is given in Appendix B.

The proposed Sandia MRDS would significantly reduce the time required to drill "probe" boreholes, which are a key element in interrogation of the postaccident mine environment and a tool for finding, sustaining, and rescuing people underground. Future development of MRDS drilling technology would leverage millions of dollars of federally funded engineering development that is ongoing at Sandia in the area of rapid drilling to produce solutions tailored for underground rescue in mines. New technology that could be leveraged from this work includes a hammer drill bottom hole assembly (BHA) that could be stored at strategic locations maintained by MSHA, flown to accident sites quickly and made up as the BHA on a standard drilling string. This work could also lead to concepts for more-efficient, smaller compression systems to support rapid drilling. Once the initial system is deployed, numerous opportunities for enhancing the basic system could be developed, tested, and fielded.

1.1 MINER Act

As a result of several recent fatal accidents in underground mines, Congress passed the Mine Improvement and New Emergency Response Act (MINER Act) of 2006, which directed the National Institute for Occupational Safety and Health (NIOSH) to create a program for improvement in mine safety through the application of advanced technology. The NIOSH program is focused on further development of preventative measures and systems and on fielding new technology for enhanced postaccident rescue and recovery. One area of current interest is to develop a more mobile and faster means of drilling exploratory and recovery holes into mine spaces where personnel may be trapped.

Safety practices in the U.S. mining industry have been improving steadily since mining became a large-scale industry in the 1800s and have reflected progress in proportion to public perception and mining-industry–related legislation (Nieto and Duerksen 2008). Nieto and Duerksen (2008) noted that improvements in safety have been related to a cycle that starts with a significant accident, followed by public demand for government intervention, and then followed by legislation focused on addressing the elements of the accident. Government and technical panels focus on industry practices in relation to the causes of and responses to accidents and recommend improvements in practices and methods that lead to research and development of new technologies. Thus, significant programs to improve mining technology are often related to legislation spurred by significant accidents. The MINER Act of 2006, an amendment to the Mine

Act of 1977, resulted in significant safety-technology research increases in response to a series of accidents, starting with the Sago Mine accident (see Appendix C for details) and continuing with a year in which 47 people died in mining accidents (Tien 2008). It was designed to improve safety, health, and accident preparedness of all mines, emergency response and to expand the powers of MSHA, while increasing the strict legislation governing mine operators.

The MINER Act was widely endorsed by both parties of Congress, by mine-safety professionals, by miners and mine operators, and by developers of safety technology. Some states initiated their own legislation designed to address issues on which they were focused, and the House passed the Supplemental Mine Improvement and New Emergency Act (S-MINER) to improve MSHA's responsiveness and reinforce mine safety following the Crandall Canyon mine accident (Tien 2008). Some provisions of the MINER Act of 2006 included improving the experience and training of rescue teams (two of which must be on standby for each mine) and requiring development and continuous updating of emergency response plans for each mine. This report recommends using an MSHA web site for improvement of emergency response preparedness and action during accidents and recommends adding a training unit for emergency response drillers. The National Mining Association (NMA) responded to the 2006 accidents by creating an independent commission of mining and safety experts that decided more research was needed in rescue-and-escape training and communications, emergency response, and rescue capability, among other suggestions (CDC 2009). Funding for the present study by NIOSH has been influenced by the cycle of events mentioned in the first paragraph, making the MINER Act a significant driver for Sandia's present engagement.

1.2 Mine Rescue Drilling System Overview

In its simplest representation, the proposed MRDS will consist of two distinct systems, although the systems may share resources and capabilities towards accomplishing their objectives. First, a probe hole drilling system will be rapidly mobilized in response to a mine entrapment and used to probe mine spaces for trapped miners. This drilling system will be used to do the following:

- Provide life support operations (air, water, food)
- Establish communications
- Survey mining conditions

Based upon the success of the probe hole drilling operation, a rescue shaft drilling system will be used to provide a shaft for miners to escape to the surface. The most effective application of this system would also include improved communications during emergency events, training for rescue-response drilling contractors and improved protocols for the staged application of existing and potential new technology for rapid drilling. The earliest steps in the MRDS tool and methodology development focus only on the probe hole drilling and would be to design a specialized BHA that would be used with a conventional air hammer drilling rig adapted to use higher than standard pressure. The tool would be sized for drilling the probe hole. Sandia would also develop methods for adapting the commercial rig and for other potential enhancements to existing protocols and support elements.

1.3 Sandia National Laboratories' Role

Sandia has been tasked with conducting an initial engineering study to conceptualize the design and eventual development of an MRDS (work scope provided in Appendix B). Sandia has been developing drilling technology for programs such as geothermal and fossil energy recovery for over 30 years. Recently, Sandia has been exploring the development of compact, mobile, ultra-high-speed drilling systems for a variety of potential applications. One application of great interest is to support future mine rescue efforts with the capability to locate a drilling system over a portion of a mine where personnel are believed to be trapped and rapidly drill one or more exploratory holes to access the mine and provide the rescue team with the ability to explore those areas with remote camera systems and provide life-sustaining supplies to those who may be found. Current commercial drilling systems are generally too large and bulky to be deployed rapidly over a mine location, which is often in rugged terrain with few, if any, access roads. Based on recent experience, it can take several days to mobilize and set up a drilling system onsite because of the need to blade access roads and create a large working pad for the drill and auxiliary equipment. In addition, commercial drilling methods are mainly designed to access product (water, gas, oil) and are not optimized for speed that is critical in a rescue operation. Rescue efforts could potentially be far more effective, if a drilling system could be airlifted to a location, set up, and drill into the mine in a matter of hours. This could be accomplished with a spectrum of solutions ranging from a new technology BHA attached to a conventional drill rig to a new technology "made for purpose" drilling rig.

Sandia has conducted a concept design study towards the eventual development of an MRDS that meets technical and program needs. The work proposed in this task is summarized in Appendix B and generally followed the technical approach below:

- Define requirements through discussions with NIOSH, MSHA, the drilling industry, the underground mining industry, mine rescue specialists, and others as needed to establish system operational and design requirements

- Survey available technologies applicable to an MRDS through ongoing presence in the drilling industry through government-sponsored drilling research and development, interaction with industry and academia, and awareness of development requirements for drilling technology.

- Perform trade studies of available options by examining trade-offs to narrow the potential design space and optimize the system concept to meet the functional requirements.

- Develop a concept design based upon findings that meets the foregoing requirements and is compatible with the envisioned overall system concept for the MRDS.

- Develop a concept of operations (CONOPS), a high-level vision of the how the system will be maintained, tested, deployed, employed in a rescue operation, retrieved, and stored through its life cycle.

- Define a system development path that outlines the developmental stages that could be successively built upon to achieve a full prototype system with the ultimate goal of a "fit-for-purpose" mine rescue system.

- Conduct testing in parallel with the aforementioned activities to validate the conceptual design approach.

Because it is critical to get some capability in the field as early as possible, full development is expected to occur in phases, with each succeeding system generation being a step improvement over the past. Sandia also expects to leverage recent research and development efforts related to the development of high-speed rock drilling. Depending on the results of these efforts, plans will be formalized for future development.

1.4 Scope

The present report describes the results of Sandia's MRDS design study and describes in detail a proposed approach for the staged development leading to ultimate MRDS solutions:
(1) development of rapid drilling MRDS equipment, (2) structuring improved web communication through the MSHA web site, (3) development of a CONOPS for employment of the MRDS with existing drilling technology in emergencies, (4) deployment of advanced technologies to complement mine rescue drilling operations during emergency events, and (5) an outline for the potential future development of an integrated technology for the MRDS. This phased approach allows for rapid fielding of a basic system for improved rescue drilling, with the ability to improve the system over time at a reasonable cost. The present report presents the results of preliminary studies of performance requirements for an MRDS based on mine accident reviews, geological provenance of coal deposits, and current drilling practices and equipment. These background data form the basis of our initial requirements definition that would be expanded in future studies.

2 Background

Mining contributes significantly to the U.S. economy and security, producing products and providing jobs in the production of mined materials and products and services that arise from them and providing jobs in transportation and consumption of electric power in the case of coal mining. However, this source of security and prosperity comes with a cost in the area of potential threats to worker health and safety. Underground mining is a dangerous operation, and the federal agencies tasked with oversight of coal mining recognize that improving technologies that impact miner safety are of prime importance. Mine rescue efforts have demonstrated that when accidents occur, wellbore drilling is one of the most important means of increasing the chance miners trapped underground will be found, receive sustenance, and be more likely to survive. Wellbore drilling can replace sending rescuers into uncertain circumstances in the early hours of accident response, thus not unnecessarily endangering the health and safety of first responders. The concerns of operators, miners, and regulators, along with security and economic impacts of the mining industry, compel better solutions to safety issues. A review of recent accidents clearly illustrates hazards and shows the role of wellbore drilling in subsurface interrogation and rescue. The importance of increasing the speed when emplacing boreholes during accident response cannot be overemphasized. Time saved is lives saved.

The following discussion illustrates the importance of mining to the U.S. economy, discusses the dangers of mining using recent accident histories, mentions previously attempted technological approaches, and briefly discusses training on the national level. Attributes of the existing system, lessons learned from mining accidents, and the current state of technology and training provide background data for analysis of possible advances MRDS technology and the path selected by Sandia for development of the system.

2.1 Overview of Mining Operations

2.1.1 Impact

It has been projected that "…in 2015 U.S. coal production, transportation and consumption for electric power generation will contribute more than $1 trillion (2005 $) of gross output directly and indirectly to the economy of the lower-48 United States…$362 billion of household income and 6.8 million U.S. jobs…" (Rose and Wei 2006, 3). In 2008, 86,859 people were employed in coal mining in 1,933 mining operations with the largest number in Appalachia.

According to the federal government's Energy Information Administration website, 1,171,809,000 short tons of coal were produced in the United States in 2008, and the expectation going forward is for growth in production to average 0.6% per year from 2007 to 2030 (U.S. DOE 2009, 83). Growth in production will include mines in the West (Wyoming, Montana, North Dakota, and other states) and mining higher sulfur coal in the Interior region in Illinois, Indiana, and western Kentucky since there will be more coal-fired plants retrofitted with flue gas desulfurization. Total production in Appalachia will decline slightly in the higher-cost Central Appalachian mines and shift to more production to the Interior region, the northern Appalachian basin, and South America. It is difficult to predict what will happen to coal production in the future, as much depends upon greenhouse gas emissions policies.

Clearly, the coal resources of the United States are a foundation element of our energy security and therefore our national security. Electricity is second only to food in annual sales volume for a U.S. commodity (Rose and Wei 2006). Over half of the electricity in the United States is generated by coal-fired plants and after electricity generation, steelmakers use the most coal. These two industries are key to U.S. security. The United States has abundant resources in the ground; however, actual reserves rely on market price and demand at the time of development. Coal is our cheapest fossil fuel, and policies or economic situations that would decrease its supply or increase its cost would significantly impact the U.S. economy. The Rose and Wei (2006) study estimated the economic impact of displacing (due to environmental policy) either 66% or 33% of coal-fuel generation. The calculated economic impact of displacing 33% of coal-based generation in 2015 would be a $166 billion (2005$) reduction in gross economic output, a $64 billion reduction of annual household incomes, and the loss of 1.2 million jobs.

The mining of these vast reserves requires a significant number of mining operations throughout the country. Figure 1 shows in excess of 2,000 coal mines located across the continental United States. Significantly more mines exist when all types of mining operations are counted. Figure 2 shows the distribution of mines for all types of mining across the United States. About 300,000 people work directly in mining throughout the United States, with an excess of 47,000 workers at underground locations (Figure 3). Every American uses an average 47,000 pounds of newly mined material per year (Source: NMA per NIOSH Presentation). Mining has great impact on our daily lives, our national security, and the workplace safety of the 300,000 estimated mining employees. The focus of the present study is on the safety of those who work underground in mining.

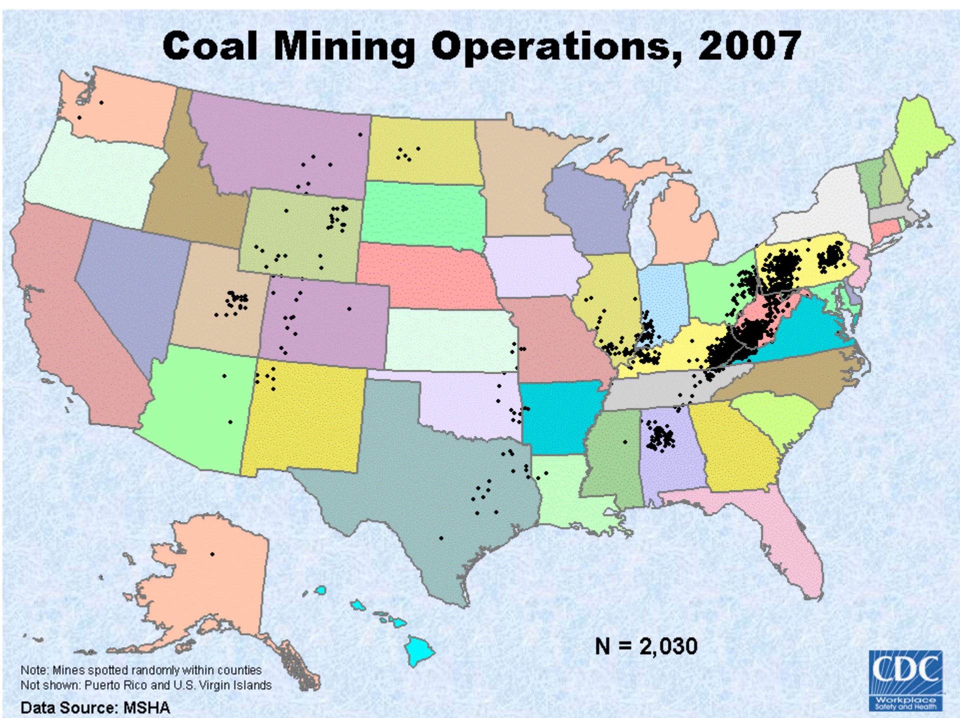


Figure 1. Coal mining operations, 2007 (http://www.cdc.gov/niosh/mining/statistics/)

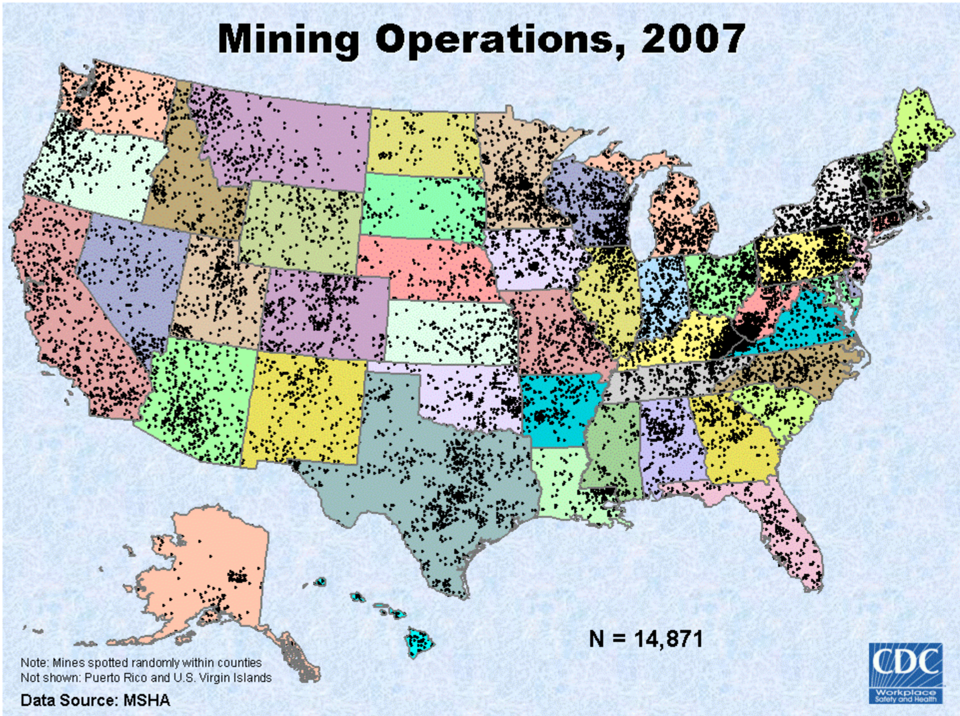


Figure 2. Mining operations of all types, 2007 (http://www.cdc.gov/niosh/mining/statistics/)

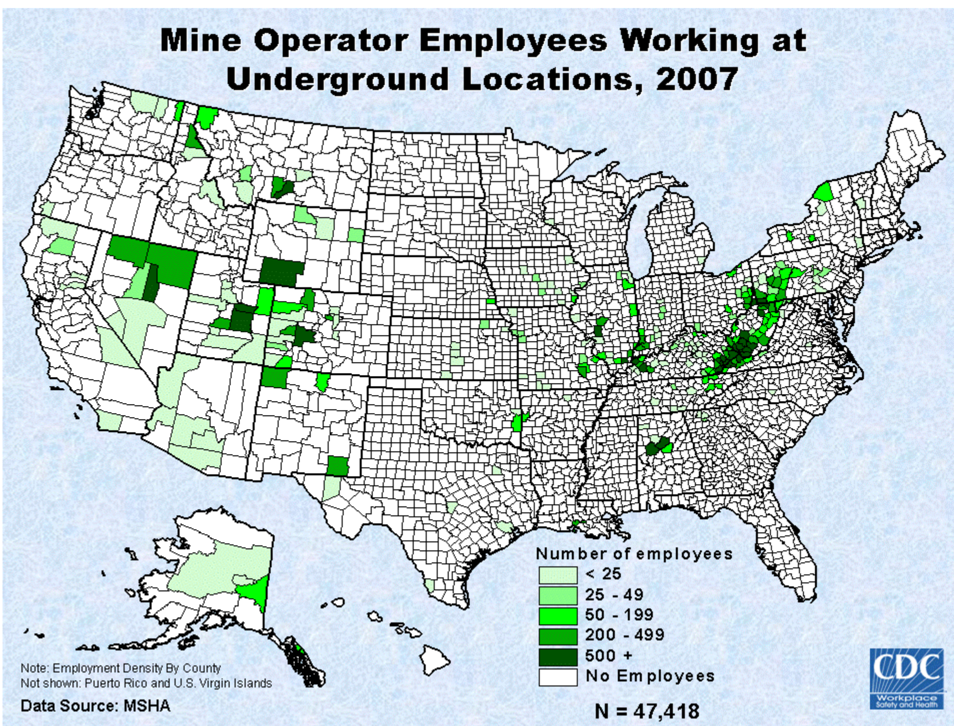


Figure 3. Mine operator employees working at underground locations, 2007 (http://www.cdc.gov/niosh/mining/statistics/)

2.1.2 Mining Fatalities

There have been great strides made in mining safety since 1978, the first year that MSHA operated under the Mine Safety and Health Act of 1972 when 242 miners died in mining accidents (MSHA web site, www.msha.gov/stats/statinfo.htm). For calendar year 2008, the loss of life was 30 for coal mining, which contributed to 53 fatalities in all mining accidents. MSHA continues to work toward no loss of life in mining operations. The 2009 year-to-date fatalities are (through October 9) 16 in metal/nonmetal and 13 in coal mining. Statistics show that compared to all private industry, with a fatality rate of 4.3 per 100,000 workers, mining is a hazardous activity with metal/nonmetal mining having fatalities of 28.7 and coal mining having 26.8 per 100,000 workers. The focus of this report is on development of a rapid-drilling rescue system that can reduce the time spent in emplacing both probe boreholes and rescue boreholes. We believe that in all mine rescues, time saved is lives saved and health preserved for trapped miners. When boreholes do the interrogation of underground conditions and supply sustenance and an exit path to trapped miners, their use also removes unnecessary risk for potential underground rescuers. Rapid drilling technology will reduce the risk from the hazards to health and safety caused by conditions that occur in rescue operations in response to mine accidents.

2.2 Recent Mine Accidents

A brief review of coal mine accidents in 2002, 2006, and 2007, serves to illustrate the fact that time saved is lives saved and health preserved when a mine accident occurs. In all but one case, boreholes were used to interrogate the subsurface and/or supply sustenance and egress. The primary benefit of reviewing those accidents for the present study is the contribution of lessons learned that apply to development and application of the MRDS. Lessons learned from those accidents are discussed in Section 3. The summaries of those mine accidents are based on the MSHA reports cited within each and are intended to capture basic events and timelines with somewhat more detailed treatment of elements relevant to the use of boreholes during accident response and rescue. The summaries are in Appendix C.

2.3 Background of Mine Rescue Drilling Systems

Since the earliest coal mining disasters resulting in loss of life, there has been interest in mine rescue technology. There are various federal acts and orders creating and guiding the federal agencies responsible for mine health and safety, and the federal agencies have solicited technology improvements from industry and others. In 1969, the Bureau of Mines accepted a proposal from the president of the National Academy of Engineering (NAE) to perform a study of technological capabilities that might be useful for mine accident survival. They came up with five technologies on which the Bureau of Mines should focus its efforts and one such technology was "…drilling rigs capable of high penetration rates to depths of 2,500 feet; one rig to probe for trapped miners with 6- to -8 inch diameter holes and the other to cut 28-inch holes for rescue." (Kravitz 1981). To this day, rapid drilling remains one of the key technologies that can improve mine search and rescue by determining subsurface conditions more quickly and by locating people and providing sustenance and rescue capsules.

In 1971, a Mine Emergency Operations (MEO) Group was set up under the Bureau of Mines and today is under MSHA. The MEO Group fields a command-center vehicle, the Mine Emergency

Unit (MEU) of volunteer first responders and brings communication and other technology to bear on the rescue. The technology includes a rescue capsule capable of bringing a man to the surface from underground. The capsule is 21 ½ inch diameter and 110 inches long weighing 650 lbs. The idea of developing a rescue capsule was likely spurred by an accident in August 1963 in Oneida, Pennsylvania, which resulted in two coal miners being rescued by being pulled from over 300 feet below ground through an 18-inch borehole using harnesses, grease, and 5/8-inch rope.

2.3.1 Westinghouse Electric Corporation – Coal Mine Rescue and Survival System

Recommendations from the NAE study discussed above became the focus of a Bureau of Mines' request for proposal that was answered by Westinghouse Electric Corporation, which won a contract to design coal mine rescue and survival equipment. The equipment served three general functions: survival (small breathing apparatus and a survival chamber), communications, and rescue drilling (U.S. Dept. of Interior 1971). The time limitation of the contract meant that their system had to be adapted from existing technology as opposed to innovative. The Westinghouse report describes their deliverable as follows:

> …two drilling rigs…capable of drilling (in terms of size and hook load, cable length, and power plant capabilities) to 2500'…The smaller of the two…the probe rig, drills an 8 ¾-inch diameter hole…The rescue rig drills a 28-1/2-inch diameter hole…Both rigs can be disassembled for airlift….by helicopter…Some parts were readily available in the industry as standard assemblies…while others had to be field modified in the Rowan yard to suit the special requirements of mobility, including dimensional constraints for various transport modes. (U.S. Dept. of Interior 1971, Vol. V, 10)

The rigs and support equipment had to be tested for use by various drilling techniques, including different circulation fluids. They then identified crews and worked on and tested plans to respond to emergencies with the rigs. A test was conducted to confirm mobility with truck deployment in rugged West Virginia conditions during winter. They were able to successfully deploy, drill with accuracy, and deploy emergency supplies to "trapped" miners through the probe hole. Rates of penetration were less than requested by the proposal, particularly at shallow depths. One problem they had was forced stoppage of drilling for enforced quiet periods for seismic test and again just prior to mine penetration, resulting in shutdown and start-up procedures adding to the drilling time. Their total time to complete the 777-foot probe hole was four days and one hour, with a drilling time of 54.1 hours. "Thus, drill penetration rate was 8.0 ft/hr or 14.3 ft/hr, depending on the base of calculation. Instantaneous drilling rate (for short periods) achieved 60 ft/hr" (U.S. Dept. of Interior 1971, Vol. V, 12). The target drilling rate for the probe rig was 100 ft/hr in 12,000 psi strength rock and 20 ft/hr in 25,000 psi strength rock, but it had a poor rate of penetration in the shallow part of the hole, with the first 100 feet taking 45% of the time to drill to total depth. This was caused by low weight on the bit and low rotating speed, which was related to the rig design not allowing normal rotating speeds until the hole was deep enough to stabilize the kelly (U.S. Dept. of Interior 1972, Vol. III, 62–63). The Bureau of Mines' target rate for drilling the rescue borehole was 17 ft/hr in 12,000 psi rock and 6 ft/hr in 25,000 psi rock (U.S. Dept. of Interior 1971, Vol. III, 6).

The two drill rigs could use almost any circulating method available at that time in either direct or reverse flow modes: dry air, air/mist, air/foam, drilling mud, or water. This made them adaptable to geological and hydrological variability. The rescue bit life was shorter than expected due to tungsten carbide inserts breaking. Both rigs could achieve vertical drilling within the required 2 degrees per 500-foot average deviation in horizontally stratified formations, but they observed that drilling through strongly dipping beds could require additional directional drilling capability (U.S. Dept. of Interior 1971, Vol. III, 63). They could drill the probe hole directionally with added commercially available downhole tools and suggested having directional drilling capability to reduce site preparation work at difficult sites. Added equipment recommended included air hammer drilling equipment, drill string weighting equipment, downhole hydraulic motors, higher-capacity air compressors, a means to quickly change circulation methods, and increasing the efficiency of tool handling. Westinghouse recommended that for future applications they modify the rescue rig to perform the probe hole function instead of having two rigs and recommended looking at applications of smaller drilling technology (U.S. Dept. of Interior 1971, Vol. III, 64).

The Westinghouse report made observations relevant to the technical requirements for drilling. They observed that preparing a pad for a rig vertically above an underground target in rugged terrain can consume a large amount of time as can drilling the top part of the probe hole without unacceptable deviation from vertical (U.S. Dept. of the Interior 1971, Vol. III, 61). They also noted that procedural integration of the rescue subsystems is time consuming. Though they were tasked with developing two separate drill rigs, one for probe and one for rescue, they observed that that resulted in more, larger, and heavier equipment than would otherwise be necessary for the operation. As required, the prototypes could be trucked or airlifted (military or heavy-lift helicopter), though the study noted that the 18–36 hours required for disassembly, reassembly, and transport limits the usefulness of air transport. The rigs could use almost any kind of circulating method available at that time and they observed:

> Vacuum reverse air circulation is the method of greatest utility for the Rescue Rig and may have limited utility for the Probe Rig. Direct compressed air circulation is best for the probe rig, in most cases, providing more positive hole cleaning and fewer operational problems, and confining site preparation and rig-up to the basic rig trailer. Optimizing vacuum drilling with both rigs will require experimental testing with air flow rates and with water and other additives. (U.S. Dept. of Interior 1971, Vol. III, 62).

They also observed that lack of full winterization of the prototype equipment was detrimental to efficiency, safety, and comfort and recommended doing it in the future since it must operate at temperatures down to -20°F.

Interviews with NIOSH/MSHA personnel indicated that the cost of maintaining the probe-and-rescue rig became prohibitively expensive. These systems have now fallen into disrepair, although the miner rescue capsule, referenced in the Quecreek description (Appendix C) remains available for future rescue operations and is currently on display at the Quecreek Mine Rescue Foundation museum at the site of the rescue.

2.3.2 Other Known Work

Center Rock Inc. of Berlin, Pennsylvania, produces low-profile drills and hole openers ranging from 20–114 inches, as well as hammers. According to their web site, the low-profile drill features a group of individual 6-inch-class low-volume air hammers, each impacting a 7.875-inch self-rotating hammer bit that can drill hard or soft rock. They feature air hammers with a valveless design and porting configuration that allows water injection and that can drill wet or dry. Bit sizes are 60-24 inches, and they operate with variable pressure of 200-400 psi. They also produce custom-designed “AirOnWheels™” trailers to supply air and foam injection.

2.4 Mine Rescue Training

Mine rescue training began in 1910 when the U.S. Bureau of Mines was in its first year. Today’s mining industry, industry groups, regulators, and mine rescue groups encourage high-quality rescue methods through contests where groups in various rescue specialties compete to display their abilities. The areas of expertise tested and the elements of capability measured illustrate the areas where improved technologies and processes could make a difference. Miners compete in field problem solving where they are presented with a hypothetical mine-emergency problem and rated on how quickly they complete specific tasks while demonstrating knowledge of standard mine rescue procedures. They have bench contests where specialists who maintain rescue equipment must check for defects in equipment and fix them quickly. They also have first-aid contests and contests for preshift miners who examine the mine layout before the work shift to identify and remove hazards. There are state, regional, and national mine rescue contests that are most often put on by a combination of entities such as rescue groups, MSHA, and state offices concerned with mine health and safety.

At present, there is no national-level training for emergency response drilling contractors. Sandia’s MRDS concept includes developing improved protocols for staged application of various drilling technologies in various emergency circumstances to improve results for more rapidly emplaced boreholes. This approach would include training for drillers within the existing national framework of mine rescue training.

2.5 MSHA Framework for Emergency Response Communication

MSHA has well-established protocols for emergency response. Each element of the first-responder community is well versed in its roles and responsibilities as it fits into the MSHA emergency response framework. For example see “Responding to a Mine Emergency” by MSHA (http:www.msha.gov/regs/complian/guides/MineRescueTeamsIG.asp). MSHA also maintains a website (**www.msha.gov**) to handle its high-level day-to-day communications with the mining industry. When a mining emergency occurs, MSHA can quickly establish control through a 103(k) order (of the Mine Act) which results in setting up a command center manned by a variable cross section of representatives of the involved parties, including MSHA, mine operators, rescue groups, regulatory representatives, and others including miners’ representatives. The chief means of communication coordinating the command center with responders, contractors, mine personnel and others seems to be telephone, supplemented by e-mail and fax. In the present study, Sandia will discuss potential enhancement of the role of the MSHA web site in communication during an emergency event. Throughout Sandia’s discussion of mine rescue response, it is understood that all responders must operate within MSHA's emergency response framework and must follow their protocols. The integration of the MRDS within the MSHA emergency response framework is illustrated in Figure 4 (MRDS-related events are in the blue boxes).

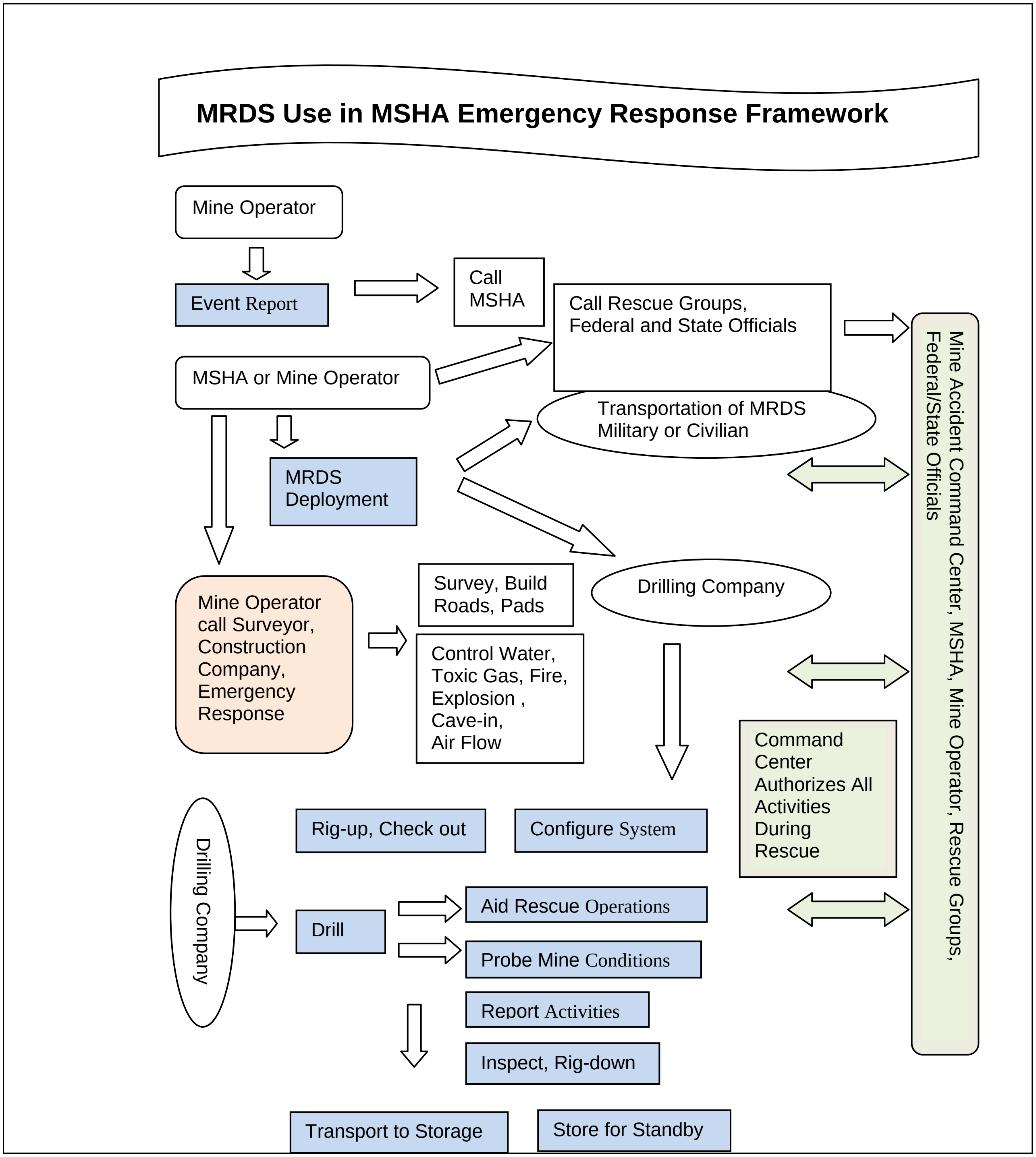


Figure 4. MRDS application within the mine rescue framework.

3 Requirements Definition

Defining the requirements for the MRDS is an important task as it establishes the operational and performance parameters for the eventual system development. The requirements definition for an MRDS comprises the definition of the task to be accomplished, the operating environment in which the system must accomplish its task, and the technical elements that enable it to become an engineered system that can accomplish its task. Definition of the operating environment in our preliminary study comes from interviews with the customer, NIOSH, and reviews of recent mine accidents including assessment of the MSHA emergency response framework. Existing drilling technology, including current drill-rig capabilities and the nature of critical support equipment and infrastructure also bears on the operating environment and those will be discussed in the following section focused on a technology survey. Communications under the current MSHA emergency response framework will also be discussed in more detail in another section. Lessons learned that bear on the development of the MRDS will be discussed in this section, and they support our recommendations for needed developments to more deeply assess some of these areas.

3.1 Approach

To develop requirements for the MRDS, Sandia used a three-part approach consisting of the following: First, interviews were held with personnel from NIOSH and MSHA to discern their perception of requirements that the MRDS must address. Discussions were also held with experts from the mining and drilling industry to discern capabilities and requirements. Secondly, recent mining accidents were reviewed for information relevant to operating in the MSHA emergency response framework, relevant to how boreholes were used and how quickly they were emplaced, and for information on the real-world logistical situations in which an MRDS must be operable. Lessons learned are captured in this section from the following studies:

- Quecreek, Pennsylvania
- Sago, West Virginia
- Darby, Kentucky
- Crandall Canyon, Utah

Finally, other operational environment elements were identified from the overall context of the task and included requirements such as “typical” geologic sections and disrupted mine conditions, explosive atmosphere, mine flooding, and other anomalies that must be addressed for a successful overall system.

3.2 Requirements per NIOSH Interviews

Personnel from Sandia met with NIOSH/MSHA personnel to solicit their input on requirements necessary for an effective MRDS and to hear their suggestions for sources of background information relevant to the problem. The following list captures the key suggestions from those discussions.

- Review accident reports
    - Quecreek, Pennsylvania
    - Sago, West Virginia
    - Darby, Kentucky
    - Crandall Canyon, Utah
- Get probe down as soon as possible
- Use three-fold approach
    - Deploy fast-response drilling system
    - Probe mine conditions
    - Drill rescue hole and conduct rescue
- Define rescue system interfaces and offer rescue drilling training
- Take capabilities approach to identify drilling contractors who can operate the rescue system
    - Rely upon local expertise and capabilities
    - Ensure broad geographic success of the rescue drilling system.
    - Make interface as simple as possible with incentives to connect.
- MSHA would maintain the rescue system, but hardware maintenance costs should be minimized to be commensurate with their annual budget.
- MSHA has jurisdiction, but mining company would use the system during rescue operations.
- Drill fast
- Go straight
- Hit the entry (approximately 18 ft wide)
- System reliability is important (cannot lose bits downhole)
- Probe hole diameter
    - 4-inch-diameter hole for MSHA communications probe
    - 8-inch-diameter hole for MSHA TV probe
    - 4-inch diameter is acceptable, 8-inch is better
- Depths
    - 2000 ft depth is worst case
    - 725 ft is median depth
- Eventually, NIOSH would like to have four (4) rescue drilling systems, located as follows:
    - Pittsburgh, Pennsylvania
    - Beckley, West Virginia
    - Price, Utah
    - Backup Unit (location to be determined)

3.3 Requirements Summary

The focus of lessons learned for this assessment will be those related to using boreholes as probe holes to find miners, collect information on subsurface conditions, and send sustenance to miners and also as rescue boreholes in which to send down a rescue capsule and bring up miners. The focus will also include lessons learned about the emergency response framework in which the MRDS would be deployed and operated and MSHA response protocols and communication methods. The discussion of disrupted mine conditions postaccident also contributes to our assessing technology requirements. Each subsection will discuss the background information collected, implications for an MRDS that bear on its operating environment, or requirements for a successful technology.

The most important lesson to be learned from past experience is that time saved means lives saved. In many accidents, miners survive the initial event and can often find livable space in which to wait for rescue; however, conditions adverse to survival must be mitigated as soon as possible, and miners must be retrieved as soon as possible to ensure the best outcomes. The many elements that inevitably stretch the time to get a borehole going and to reach total depth show that improved drilling speed is a factor where technological advance can reduce rescue time.

3.3.1 Mine Rescue Protocol Compatibility

The study of recent mining accidents provides information on the MSHA emergency response framework, including communications methods. This information illustrates the framework in which responders operate when providing personnel and equipment. It also shows that there are many communications required with entities that are located locally and across the country, with the need of constant updating of information as the situation evolves. Sandia's recommendations include enhancements to the communication methods using the information on the response framework for the CONOPS (concept of operations) for an MRDS.

Though scenarios vary and many entities are involved in every mine rescue, orders, plans and command centers are established that guide what occurs. Basic mine rescue protocol has evolved over time (U.S. Dept. of Labor 2007a). Generally a command center is established that is headed by the mine operator. The command center includes state and federal officials and rescue groups and can include miners' representatives. Usually early on, MSHA issues a section 103 (k) order that requires submittal of a written plan from the mine operator that must be approved by all entities in the command center. All decisions related to rescue are made through this method. MSHA deploys their MEU with its trained rescuers and specialized equipment, including the rescue capsule, to disasters. Rescuers may not be allowed underground if conditions are unknown or are known to be very threatening or unpredictable. When rescuers do go in it is with caution and by following protocol. They often establish a fresh air base (FAB) from which to work with hard-wired communications to the surface command center, if possible. They then explore the mine in a staged manner, generally exploring about 1,000 feet from the FAB, moving out from there in stages. They may need to build temporary ventilation controls as they go in. Usually, they have permissible radios and hand-held air-quality detectors. To minimize danger from subsequent explosions or toxic air, it is usual to wait for atmosphere stabilization before mine re-entry (U.S. Dept. of Labor 2007a). All of these protocols for underground search and rescue are deliberate and prescribed and necessarily take time in order to protect the rescuers and prevent subsequent accidents.

The protocol for use of the miner rescue capsule is that MSHA keeps and deploys it. The rescue capsule is not employed as widely as would be technology for an MRDS BHA for a probe hole.

There is uncertainty regarding when the BHA might be needed, which company might be called, and which crew that works for that company would be available. The most practical method for employment of Sandia's proposed BHA would involve having an MSHA entity in charge of knowing how to use the BHA, storing it in several strategic locations, and being responsible for deploying it and facilitating its use by local drillers. An expert from the company that will make the BHA might be made available to travel to an accident site if needed.

3.3.2 Effective Communications during Emergency Events

Adequate communications links are necessary during an event to support the most rapid possible response from drilling and drilling support (compressors, etc.) contractors. Communications are used to transmit orders, coordinate equipment transportation and setup, and support all surface operations. Section 2.5, presented previously, discusses modifications that might be made to existing communication tools to speed up key processes involving personnel and equipment coming into the area of an event. This is an area where new methodology can reduce time to borehole emplacement by enabling more rapid response by contractors who can get some necessary information before they arrive at the site. Section 6.3 discusses possible improvements in communications tools.

3.3.3 Efficient Logistics and Transportation

Where and when the next mining accident will occur is an unknown. Because of this, difficulty in logistics and transportation exists. Underground mining accidents can occur during inclement weather, over rugged terrain with limited to no road access, and at relatively high elevations and during periods of low or high ambient temperatures. All these variables can compromise a successful airlift operation.

Airlifting components such as compressors and boosters to remote sites poses numerous challenges. These challenges can be broken up into two categories: (1) logistical steps required to make sure equipment can be delivered at "a moment's notice" and (2) equipment limitations such as weight capacity, dimensional envelope, and distance to be flown.

The BHA proposed as part of Sandia's recommended development effort is a relatively compact piece of equipment that can be airlifted to a site. Storing it and packing it for deployment would be relatively easy as well. As part of work beyond the initial deployment effort, Sandia proposes to investigate the feasibility of new technology to reduce the size and mobility of other drilling elements such as compression systems and a made-for-purpose drill rig of a compact size.

3.3.4 Survey Availability (Surface, Mine)

Identifying where to drill a probe hole is an important criterion for an MRDS. Given the significant time investment necessary to locate the surface equipment, spud the hole, and drill to depth, the time necessary for identifying the preferred drilling location is well spent in the long run. Ideally accurate mine surveys should be available with correspondence to identified surface features before an accident event.

Determining when and where investigative boreholes will be drilled can be a long, complex process. The mine operators are likely to call in the surveying company that surveyed their mine and a drilling company soon after an accident. Getting a good survey can take a lot of time.

They must use surveyed maps of the surface and subsurface and Global Positioning System (GPS) equipment is available and resurvey, sometimes by several methods. This activity is primarily run by the mine operator, but final decisions on where and when to drill go through the command center. When miners are found underground after an accident, then there could be surveying decisions related to emplacing a rescue borehole.

3.3.5 Find Men Underground

Unless they are able to communicate after the accident, determining the probable location of a trapped or disabled crew underground depends on their work assignment compared to the time of an event, supplemented by chance observations of those who were able to communicate to the surface after an accident. Other indirect information on probable location includes their training and whether they could perform recommended activities, including following the most direct escape routes or whether they had to follow an unknowable route left after underground disruption. It is always possible that they had to barricade in an area where conditions seemed survivable, especially if they were a long way in or if some disruption was known to have occurred between them and an escape route. Rescuers often try to work out the men's probable responses to an accident by listing what the miners probably knew of conditions in the mine and guessing how the miners would use that knowledge to plan an exit. They use other indirect methods such as tribal knowledge of what most often causes ignition, therefore where it likely occurred.

MSHA has a seismic system that produces sound on the surface with small explosive charges to which miners should respond by tapping. MSHA's sensitive listening system requires total quiet on the surface for 30 minutes, but at Quecreek they didn't think they could shut off the air compressors for that long. A second system was used and was able to detect the Quecreek miners tapping, but the miners were listening for the explosions from the other more sensitive system (US Dept. of Labor, 2003).

The Sago Mine disaster is an example where deciding the location of the first borehole was very time consuming. There were delays getting a mapping or survey grade GPS onsite, and when it arrived they were unable to get satellite signals or radio communications adequate for accurate results. They finally used surveying from permanent markers. The first borehole in this case was not successful in locating the men and another borehole had to be abandoned because of water coming into the hole (U.S. Dept. of Labor 2007a). In other cases, boreholes have missed the mine openings and hit pillars.

In the Crandall Canyon Mine disaster, the last four boreholes (of seven) were used to continue looking for trapped men after a second disaster killed three rescuers and injured six and it was decided it was too dangerous to send men underground. For these boreholes to be useful, they had to be large enough in diameter to lower equipment like a camera, a microphone, and in one borehole a small robot that fit into the 8.75-inch hole. This accident is a good example of how it is preferable to explore underground with boreholes when the mine conditions are not stable and men's lives are at stake (U.S. Dept. of Labor 2007c).

While significant improvements in communication technology have occurred recently, it is possible (and should be assumed) that trapped or disabled miners will not have a reliable way to communicate their location to those above ground. Therefore, it is likely that drilling will continue to be a common method to look for miners and a means of sending sustenance. The greatest obstacle to using drilling for rescue at this point is the large amount of equipment needed, the slow pace of borehole drilling, and the potential for explosion caused by drilling, as previously mentioned.

3.3.6 Drill Investigative Boreholes

A borehole at the estimated position of an accident is a practical way to obtain direct information about underground conditions and to possibly establish communication with trapped miners. Often multiple boreholes are drilled because of uncertainty with regard to conditions and location of the trapped miners. At Quecreek, multiple rigs were drilling holes at the same time for different purposes. Most often the depth from surface to mine openings is not more than a few hundred feet and the geology is not particularly resistant to drilling, however, completing a borehole can take a considerable amount of time. The rate of penetration of a typical commercial hammer drill in these formations can exceed 100 ft/hr in these formations.

Though an investigative borehole of ~6.5 inches is the focus of this discussion, the following is observed from the Quecreek #1 Mine accident: When a rescue borehole was emplaced at Quecreek, there was significant trouble with broken drill bits, subsequent fishing, and availability of backup equipment (U.S. Dept. of Labor 2003). This slowed getting a hole down to rescue the miners. Once the hole was down, rescue of the miners went quickly. In addition to the initial investigative borehole, a larger hole was drilled as a rescue hole to accept a rescue cage. The hole was started as a 30-inch hole, which took two days to drill. They lost the bit in the hole, fishing was required, and a second hole was started. They finished the first hole but had to use a 26-inch bit when the second 30-inch bit wore out. This highlights the need for more than one BHA and replacement subelements in case wear, breakage, or loss in the hole occurs (U.S. Dept. of Labor 2003).

Other factors important to the actual time to penetrate a mine after an accident include the following: time of the decision to request a driller and decide it is safe to drill; time elapsed until a driller with appropriate equipment can be located, mobilized, and reach the site; time to determine where to drill; site conditions that impact access of the driller to the borehole location (proximity to roads, weather, terrain, restrictions caused by other equipment, buildings, etc.); restrictions on drilling rates by the command center when nearing the target depth; drilling equipment breakage or loss in a borehole with subsequent fishing, waiting on another part, or re-drilling; and coordination of drilling and underground rescue teams to avoid hazard to the underground teams from an explosion caused by drilling.

At Crandall Canyon, the first investigative borehole was with a small rig, helicoptered in from a nearby mine that drilled a 2.4-inch hole too small for a camera and that lacked directional control. It missed its target by 85 feet. Its polycrystalline diamond compact (PDC) bit was clogged and had to be cleaned to get a good air sample. The other six holes drilled there by hammer drill were 8.75 inches (below 20 feet) and were used to sample air quality, pump in fresh air, and lower a camera and a microphone. One was used to lower a robot. In two holes, they were unable to get a camera down the hole because mud blocked the hole, one at 511 feet and one only 9 feet above the mine opening. These holes were hammer-drilled, but mud still became a problem (U.S. Dept. of Labor 2007c). In another instance, an attempt to lower a robot in a 12-day-old borehole was stopped because the hole had partially closed.

Many factors affect how quickly a borehole can be started and finished. Improvement in the drilling rate is technically feasible, whereas many other factors that lengthen the time to emplace a borehole are more difficult to impact through technology. Improved pre-accident planning and training in areas relevant to drilling could cut down the time for some of the factors involved. Training for drillers involved in emergency response could improve performance and introduce them to technology such as that described herein. A limited-access area created as part of the MSHA web site could provide basic information relevant to specific, ongoing emergencies such as location maps, topographic maps, and general geologic sections. Easy availability of these basic data could cut down the time to get responders up to speed and enable them to select equipment for drilling that is more suitable to the site.

3.3.7 Geology / Effective Drilling of Formations

A basic requirement of the MRDS is that it be capable of penetrating a "typical" geologic section found in coal-producing areas. The Bureau of Mines reduced this requirement to a description of the compressive strength of rock and the expected drilling rate for the Westinghouse mine rescue system described in Section 2.3.1. The requirement was for the probe hole to make 100 ft/hr in 12,000 psi rock and 20 ft/hr in 25,000 psi rock (strong quartzite). The rescue rig was to make 17 ft/hr in 12,000 psi rock and 6 ft/hr in 25,000 psi rock. With current rapid-drilling technology proposed for the BHA, these rates may be exceeded by nearly an order of magnitude.

Storage and deployment of MRDS equipment is most likely in at least four areas of the country, including Pennsylvania, West Virginia, Utah and another location to be determined. The Westinghouse study, cited previously, contained the following (U.S. Dept. of Interior 1971, Vol. III, 7–10). They designed a system with a focus on geologic conditions likely in the Appalachian Plateau and described the geomorphology as "…a dissected plateau with steep slopes of up to 45 degrees and relief of 500-1500 feet…" with thin soil and surface to near-surface rock mainly horizontally bedded sandstone, siltstone. and shale. They described the coal beds as nearly horizontal, changing to open folds and arches in some areas and varying from a few inches to 8 feet thick. They designed their drilling system (bits, collar, rig power, and circulation material) to be most effective in this type of sedimentary section. Climatic conditions arising from the latitude, steep slopes, and altitudes of 3,000–4,800 feet, along with average yearly rainfall of 35 inches, including 20–100 inches of snowfall, affected the design of equipment that had to be truck-transported over narrow winding roads with low-capacity bridges and low underpasses. In addition, the equipment had to operate at temperatures as low as -20 degrees F. The study described the hydrology of the Plateaus Province as favorable for using air for circulation because, though variable, groundwater in the higher Plateaus areas where most coal is mined is transient in fractures or is captured in porous formations. They also stated that drilling will encounter mainly sedimentary rock formations that exhibit little sloughing or caving, though some clay areas, coal zones, or hard-rock cave-ins are possibilities.

In general, the MRDS will be penetrating sedimentary sections with variable thicknesses of sandstone, siltstone, and shale and beds of varying combinations of all three, with coal beds of varying thickness, and in the northeastern United States, limestone. Therefore, the drilling method that can most rapidly and effectively drill through sedimentary rock, which may be saturated in some areas, is the technology on which we will focus for technology development. A more detailed discussion of the geology that may be encountered by the MRDS is included in Appendix D.

3.3.8 Mitigate Mine Gases and Explosions

Coal dust and methane are the primary sources of explosions in underground coal mines. Methane is very dangerous when concentrations are approximately 5 to 15% in air (Man and Teacoach 2008). A common method to mitigate explosions is to apply limestone rock dust to all surfaces within the mine. In the event of an explosion, the rock dust disperses and prevents flame propagation within the coal dust by acting as a thermal barrier (Man and Teacoach 2008, Brune et al. 2007). Brune et al. (2007) list four methods of explosion protection in underground coal mines: (1) ventilation of methane, (2) methane drainage, (3) prevention of buildup of coal dust, and (4) elimination of ignition sources. It is likely that during a rescue drilling operation, trapped miners would be in an environment with (1) minimal ventilation of methane, (2) uncertainty of methane drainage, and (3) high buildup of coal dust. Methane can be present in quantities sufficient for an explosion but not high enough to lead to respiratory failure. During mining, methane monitors are installed on certain mining equipment and warn the operator if methane concentrations above 1% are reached. Methane concentrations above 1.5% require the equipment to be disconnected from the source.

Drilling a rescue probe hole and/or a rescue shaft could pose an explosion hazard to trapped miners. The hazard exists because of a potential ignition source from the steel drilling equipment contacting the coal or installed roof bolts, and also from the possible use of air and oil for cleaning/lubricating the drilling bit. Because the MRDS's power supply equipment will likely be located above ground, electrical and mechanical ignition sources in light of a coal or methane explosion are of minimal concern for these components. However, future development and research on an MRDS should include investigation of drilling fluids that will not support combustion and/or suppress ignition. This can include mist additives and water vapor.

Disrupted mine conditions postaccident result in hazards for drilling that did not exist in the properly functioning mine. Methane and coal dust explosions can develop overpressures of 20 psi or more. Pressures generated by an explosion are well in excess of the 2–4 psi the ventilation systems can resist, so they are often damaged, and methane can accumulate where it previously did not. Ignition temperatures of coal, wood, and other combustibles in mines are less than the temperature of the flame of the explosion, and the flame speeds along at over 1,000 ft/sec. Materials with low ignition temperatures may begin to smolder or ignite. The explosion redistributes coal dust that drops out as the flame slows and cools. Large volumes of toxic and flammable gases are produced by incomplete combustion of fuels. They include carbon monoxide, carbon dioxide, hydrogen, acetylene, and ethylene, with carbon monoxide as high as 46,000 ppm. With methane explosions, postexplosion carbon monoxide can reach 80,000 ppm. When a fire burns and intensifies, carbon monoxide production grows. The temperature of a fire flame exceeds 1,500°F. The ignition temperature of methane is 1,000°F (U.S. Dept. of Labor 2007a).

These factors show that there are multiple hazards related to potentially toxic and/or explosive materials associated with perforating the mine environment. They create a hazard related to drilling that affects those above and below ground. The accident causes hazardous conditions in unpredictable patterns. Probe boreholes are a quick way to assess underground conditions.

Understanding the requirements to mitigate an explosion due to mine penetration from an MRDS is essential for a successful rescue operation. Mitigating coal dust explosions requires an atmosphere devoid of oxygen, low temperatures, and low pressures. In general, for combustion of a fuel the three requirements needed are (1) an oxidizer [usually air], (2) a fuel source, and (3) heat or an ignition source (Cashdollar 1996). By eliminating one of the components required for combustion of a fuel, the explosibility threat is mitigated.

3.3.9 Reduce Time to Rescue

The most important lesson learned from prior mine entrapments is that time saved is lives saved in virtually all situations. In drilling operations for probe holes, the right technology can reduce the time involved in (1) getting a drilling rig to a site (small ones can be helicoptered in; small, coiled tubing rigs could be stored regionally and maintained cheaply); (2) emplacing a rig in rough conditions (compact ones may not require large bulldozed pads); and (3) drilling rates (improved bits and BHAs). Probe holes can interrogate the subsurface, gathering data and targeting a rescue point during the time required for a larger drill rig to be set up for a rescue borehole. Boreholes that can find and get to men quickly and provide rescue egress save risking other lives if they can replace underground rescue.

4 Technology Survey, Evaluation & Concept Identification

This section addresses definition of the engineered system to meet the foregoing requirements that is accomplished through study of the technologies available to build the system, including the advantages, disadvantages, and trade-offs of using each technical element. It also includes defining processes through which new technologies can be studied and developed and possibly combined with existing technologies to make better systems. The result of this process is a downselect to the preferred concept to be pursued for the MRDS.

4.1 Technology Survey

A survey was conducted to identify candidate technologies that could be used to develop an MRDS. Other supporting technologies, i.e., nondrilling, will also be required to support a successful mine rescue.

4.1.1 Drilling Technology

Various elements of a drilling operation must be quickly transported to support an MRDS. A survey of these technologies was reviewed and is reported in Appendix E. Key findings are summarized here.

Rock Reduction

A variety of possible rock reduction methods could be considered for this drilling application. These include conventional drilling techniques such as rotary, top-hole (TH) hammer, down-the-hole hammer (DTHH), and unconventional systems such as thermal/spallation, rock melting, water jets, chemical dissolution, and other methods subject to past and current research. However, none of the unconventional alternatives are adequate for this application.

Generally, PDC (polycrystalline diamond compact) bits have historically dominated drilling sedimentary formations in rocks with compressive strengths up to 30 ksi. Ongoing developments have continued to extend their range into higher-strength formations. However, PDC bits have not become as common for applications outside of oil and gas drilling due to their higher cost. Percussive hammers are widely used for drilling water wells and offer the benefit of lower cost replaceable bits to this industry.

DTHH drilling is generally acknowledged to be a rapid and robust technique for drilling hard rock. A DTHH drill is essentially a jack hammer, consisting of a free-flying piston, driven back and forth by gas pressure that impacts the cutting head, which in turn strikes the rock with tungsten carbide buttons. The basic components of a DTHH drill are relatively simple and highly reliable in commercial practice. Hammer performance is primarily dependent on pressure applied to the hammer piston, air flow, and proper indexing of the bit to avoid re-breaking rock. Comparatively low weight on bit (WOB), specific power, and relatively simple surface equipment make this technique a promising candidate for high-penetration-rate drilling. In the past three years, significant effort has been focused at Sandia on design improvements to increase hammer performance and reliability, thus this is deemed to be the method with the highest probability of successfully achieving MRDS performance objectives.

Surface Rigs

Many of the rigs in the Appalachian coal region of the United States are air rotary rigs capable of drilling a few thousand feet. Most of these rigs are self-contained truck-mounted units that are equipped with an on-board air compressor that produces up to 350 psi. Higher pressures are produced by using a stand-alone booster that is fed by a compressor.

Although far less common, coiled tubing units (CTUs) are becoming more common for shallow drilling applications. Conventional industry implementations use either air or mud rotary with downhole motors to drive rotary drill bits. Commercial versions of percussive hammers on CTUs are not yet available.

Rig Hydraulics

Rig hydraulics includes both air compression for percussive hammers and the drilling fluid system for mud rotary drilling. Air-compression packages typically used in support of percussive drilling operations include compressors and boosters and mist-injection pumps. These units are often stand-alone skid-mounted, diesel-driven air-transportable units that are shipped worldwide for petroleum and mining operations. Mud pumps are available for mud rotary systems, though most appear to be less air-transportable than their air-compression counterparts.

Coal Dust Explosion Inhibitors & Additives

The risk of explosions while performing a rescue drilling operation is not limited to the area inside the mine. Regardless of the drilling technique employed, multiple explosion hazards exist when working in and around coal mines. These hazards include coal dust explosions, methane explosions, and explosions within the MRDS due to detonation of high-pressure air and oil mixtures used for drilling. Various methods of explosion mitigation could be incorporated into the MRDS and are described below.

Nitrogen production units (NPUs) are routinely used when drilling into hydrocarbon-bearing formations. These units use polymer fibers to separate the nitrogen from the ambient air stream. Purity levels of 95% are routinely achieved. Typically, twice the needed air volume is provided to the NPU to develop the required flow rates. Alternatively, nitrogen can be transported to the drilling site in tube trailers to provide a gas source.

Another approach to explosion mitigation could incorporate a nonflammable additive to the compressed drilling gas such as Krytox® or a high-expansion foam. Depending on the additives' properties, the material could also serve as a lubricant in place of oil. Use of nontoxic additive would be preferred over the use of nitrogen with respect to mine penetration because the state of oxygen in the underground environment would be unaltered. Also, drilling could commence at the same rate until the hole is finished because the need to switch from nitrogen to air is eliminated. A nonflammable additive could also mitigate coal dust ignition by wetting the dust and causing it to adhere to the additive. The coal dust trapped in the additive would be carried to the outside environment by the normal drilling process. For any additive used, a system must be engineered to incorporate the additive with compressed air. Krytox®, available from DuPont™, has not been tested for inhalation health hazards so additional research is needed to check for health effects (including respiratory) due to relatively short-term exposure.

Sandia is pursuing development of high-temperature lubricious coatings for percussive hammer applications to eliminate the need for lubricants in the air stream. Initial trials with the coatings have produced promising results to date.

Wellbore Casing

Casing is introduced to the wellbore when required for stabilization in the presence of sloughing in the wellbore or when drilling through water-bearing formations. Some percussive hammer systems are compatible with casing advancement systems that allow the casing to be advanced coincidentally with the drilling of the wellbore. These systems are primarily intended for drilling the loose soil overburden. In a mine rescue drilling situation, keeping the hole open is critical, thus casing systems should be considered when circumstances dictate. The MRDS design should then be compatible with the potential use of a casing system.

Drilling Diagnostics Subs & Advisory Systems

Drilling diagnostics systems monitor various drilling parameters during the drilling operation to aid in determining the performance and efficiency of the drilling process. These systems allow the drilling process to continue according to a deliberate plan. Knowledge of downhole conditions is the best indicator of trouble in the drilling process. Avoiding trouble is the best way to avoid “flat time” on a rig—which is when it is not producing additional hole. Processes can be monitored by an advisory system that makes judgments of the drilling data to aid the driller. This feedback can be based upon secondary parameters derived from the collected data. These systems are often system specific. Appendix F contains detailed information regarding drilling diagnostics measurements, subs, and advisory systems.

4.1.2 Communication Technologies

For a rescue to be successful, effective communication is required between various parties involved in the event. This applies to communications on the site-, local- regional-, and national-level to facilitate the rescue. Internet-based systems are the best current technology likely to add speed to communications, enable communications over wide areas to multiple entities concurrently, and lessen the workload of individuals who presently communicate vital information by telephone or fax during accident events. Later sections of this report discuss web-based communication in more detail.

4.1.3 Transportation Options

Ground transportation is the most readily available means to transport a drilling system to a rescue site. However, a number of commercial drilling system components have airlift capabilities to support the energy services market. A discussion of modern day helicopters and their lift capacities is summarized in Appendix G. However, the availability of larger airframes is limited, and the reported lift capacities fall off rapidly with increased elevation. Most equipment can be packaged so it is consistent with conventional airlift capabilities.

4.1.4 Logistics

Improved communications have resulted in improved logistics responses in many industries. The combination of improved communications, transportation efficiencies, and case studies will provide insight into preferred logistical models that could be applied to the MRDS.

4.1.5 Emergency Response System Analogs

Various emergency response systems exist that can be used as analogs to tailor a design to rapidly deploy an MRDS in the event of a mine incident. These systems should be reviewed for desirable features as phased development of the MRDS continues.

4.2 Technology Evaluation

In this section, the technologies described in the previous sections and appendices will be compared to downselect to the preferred technology to be recommended for an MRDS. Trade-offs and the merits of using the technologies are discussed.

4.2.1 Quick Response versus High-Speed Drilling

In a mine rescue drilling situation, the preferred solution is not just about high-speed drilling. Reducing the time from entrapment reporting to successful rescue is a more important metric. The emergency response time for drilling contractors is usually quick, but factors such as drill-site selection and surveying time can extend the time to rescue. Of these factors, improvement of the drilling rate is most amenable to technological solution at this time; however, rapid-drilling systems of the type Sandia proposes are not common. Getting an MRDS to the site will likely be slower than the response time for standard drilling operators. There are trade-offs to be considered between the slower rate-of-penetration (ROP) systems and the proposed faster ROP systems. Generally,

- shallow depths may be reached more quickly with fast-response, slower ROP systems and
- greater depths may be reached more quickly with slower-response, faster ROP systems

Hence, depending upon the rescue scenario, either logistics or high-speed drilling may be more important to the rescue effort. As an example, consider the depths of entrapment in two recent cases. In the case of the Quecreek entrapment, conventional drilling technology was adequate to sustain life support. Crandall Canyon, on the other hand, could have benefited from a high-speed, directional drilling system mobilized from a distant location to the rescue site. Figure 5 highlights the trade-off between fast response with slower ROP and a somewhat slower response to start of drilling but a faster ROP. This comparison highlights the importance of an advanced capability with a possible longer deployment time over a more conventional technology that is readily available. In general, however, both of these parameters must be optimized to reduce the time to rescue.

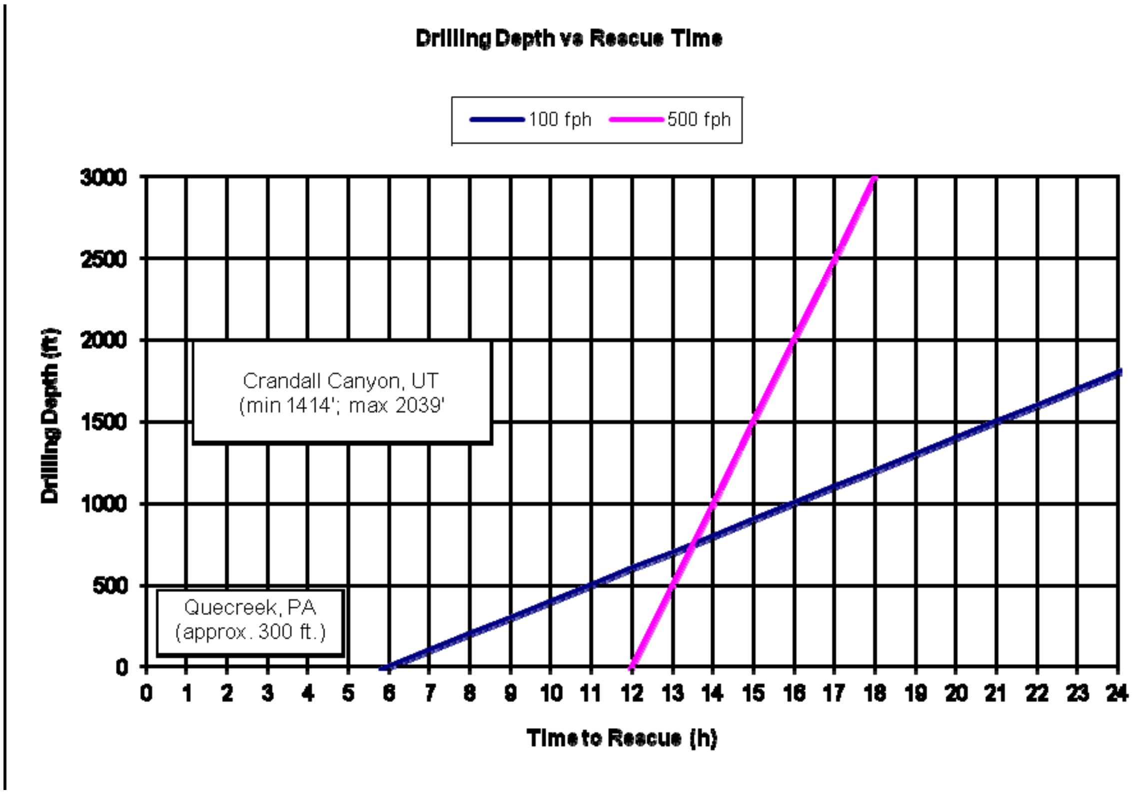


Figure 5. Dependence of time to rescue on time to setup, drilling depth, and drilling rate (Recent entrapments are referenced for depth only and not actual drilling performance conditions).

4.2.2 Deployment of Readily Available Regional Capability versus Mobilization of Specially Trained National Resources

Consistent with the balanced-solution priorities discussed above, a decision must be made during an entrapment between relying upon local capability and deploying a nationally available asset or advanced team to perform the rescue. While the readily available capability can be onsite to commence drilling, the more distant expertise may have specialized training to support the breadth of conditions that may exist in the entrapment. The benefit of the total solution should be compared with the risk in relying solely upon it for the solution.

4.2.3 Rock Reduction Method

As noted in the technology survey, percussive hammers are capable of drilling at high penetration rates. In the context of the mining industry, percussive hammers offer several additional benefits over competing options. These are listed below along with several supporting arguments.

- Percussive hammers have applicability and versatility for the application
    - Can drill a variety of rock types
    - Overburden drilling options are available
    - Many size options exist
    - Can be used to drill both probe and rescue hole

- Percussive hammers are widely available
  - Standard equipment for mine operators; also widely used by water well drillers nationwide
  - Percussive drill rigs are readily available
  - Compressors are readily available
  - Transportability (Air rotary can be onsite quickly)
  - One truck has it all
  - Very mobile
  - Do not require significant mud / water
  - Do not require drill collar as driven by top drive systems
- Performance enhancements are achievable

Linear scaling of commercial results for the specific power delivered to a DTHH (energy per unit time delivered to the rock surface by the bit) predicts the required input to the bit increases in proportion to the penetration rate. To increase the penetration rate of conventional hammers represents a significant increase of the power consumption of commercially available designs. Achieving this specific power level is primarily dependent on the manipulation of two parameters: (1) impact energy per blow and (2) impact frequency of the bit. Both parameters are effectively dependent on the piston mass of the hammer, the air pressure supplied to the piston, the air flow supplied to the hammer, frictional effects, and energy transmission efficiency of the rock/bit impact. A comprehensive analytical and experimental program will be required to improve performance beyond conventional practice.

4.2.4 Conventional versus High-Pressure Drilling Technology

Drilling at high pressures requires that additional equipment be transported and configured and limits the contractor base that can be relied upon to support rescue efforts. The benefit of the high penetration rates afforded by this capability must be weighed against the cost to produce it. Alternative technologies may be pursued in subsequent project phases to generate the compressed gas necessary for operation.

4.2.5 Air versus Nitrogen Drilling

The benefit of drilling with nitrogen is that it affords the opportunity to operate at higher pressures without the autoignition or explosive danger associated with air drilling. This requirement also mandates that additional equipment be transported to the drill site. It may be a target for an alternative technology developed in future phases as well. Nitrogen must be used with care as it will act as an asphyxiate both on the surface and in the mine spaces.

4.2.6 Casing Technologies

Wellbore casing will be required when drilling some formations. Some drilling technologies, e.g., casing advancements systems used with percussive drilling, are more amenable to a mine rescue drilling scenario.

4.2.7 Explosion Inhibitors

Mixtures added to the injection line to suppress explosion and auto-ignition conditions will have to be transported and metered to ensure correct application. While effective, these mixtures will add complexity to the overall solution, however the trade-off is that they enhance the safety of the drilling operation under potentially explosive drilling conditions.

4.2.8 Advanced Capability Deployment

Deployment of other capabilities may be needed to execute an effective solution. These systems include drilling diagnostics and directional drilling capabilities. While offering advanced capabilities, these services may complicate the system and reduce reliability.

4.3 Technology Downselect or Technology Focus

It appears that percussive hammers offer the best opportunities for a comprehensive, versatile MRDS as they are currently widely in use by the mining industry, offer high-penetration-rate drilling with numerous opportunities for improvements, and are compatible with many mine-rescue scenarios. Additionally, many mitigate the issues discussed previously. However, it is first necessary to demonstrate that this technology is capable of penetrating the formations that may be encountered in typical mine rescue applications. This is the subject of Section 5.

Other technical issues to be addressed include the balance of the drilling system supporting the advancement of the BHA and the preferred engineered system. This topic is subsequently addressed in the Section 6.

5 Preliminary Concept Development and Demonstration

5.1 Objective

To assess percussive hammers as a candidate MRDS technology, a preliminary evaluation is necessary to prove their capabilities in typical coal-bearing geologies and to demonstrate the potential improvements that can be realized by developing high-performance capabilities. Sandia maintains an ongoing research program, sponsored by the Department of Energy, to address improved methods of hard-rock drilling for improved energy resource recovery. One of these programs specifically addresses geothermal drilling and requires improved technology to penetrate hard, high-temperature abrasive rock. Since percussive hammers are not routinely used for geothermal drilling, Sandia has initiated a project to improve percussive hammer technology for this application with a technology focus of exploring the limits of high-penetration-rate drilling. Most of the research is focused upon penetrating granitic rock with high quartz content, typical of geothermal drilling conditions in igneous rock. This ongoing research is herein leveraged to develop solutions applicable to the development of an MRDS.

To be valid for the MRDS, this percussive hammer evaluation will address the following:

- Typical drilling performance with conventional hammers
- Performance improvements available with high-performance hammers
- Range of penetrable rock types

5.2 Conventional Hammer Evaluation

Sandia has partnered with Numa Hammers (Thompson, CT) to explore the limits of conventional percussive drilling technology. This collaboration allows hardware to be developed, evaluated, and tested by Sandia to assess capabilities and limiting technological barriers. Generalized results of this evaluation are reported here, although many of the hardware details are not disclosed as these are proprietary to the organizations involved. Much of the background work and test platform development used in the evaluation of hammer technologies has been sponsored by other federal sponsorship and was leveraged to assist in this study.

To evaluate the expected performance of conventional hammers, Sandia previously conducted testing to establish baseline hammer performance. As part of this testing, a thermodynamic model of the hammer cycle was developed to evaluate the relative influence of each of the parameters involved in the hammer operation. The model is described in further detail in Appendix I. This thermodynamic model provides an estimate of the power delivered by the piston to the bit shank. The model can subsequently be used to evaluate the overall hammer operation to identify areas where the efficiency of the gas cycle can be modified to improve the overall hammer performance.

Appendix J addresses the various parameters involved in the interaction of the hammer bit with the formation. A number of parameters can be addressed when considering overall bit performance. This evaluation allows an upper limit on hammer penetration-rate performance to be predicted, given a prediction of the power delivered to the bit shank by the piston. Hence, both the thermodynamic model and the rock bit interaction parameters can be used to assess the performance of the system.

Small diameter hammers were evaluated to reduce hardware material-development costs and evaluation requirements. Most of these were 3-1/8-inch-diameter hammers with 3-1/2, 3-3/4, and 4-inch-diameter bits. Based upon the NIOSH request to have a larger diameter wellbore, a 5-½-inch-diameter hammer was evaluated as well. Various bits were designed and built, according to the available parameter variations described in Appendix J, and tested on the 3-1/8-inch-diameter hammers using the Sandia test rig. The parameters prescribing the designs of the bits were varied to allow the influence of various bit-performance parameters to be evaluated.

5.2.1 Test Rig Description

Using funds from the leveraged project previously mentioned, Sandia has developed a test rig to allow evaluation of percussive hammers in representative rock formations. The facility, pictured in Figure 6, allows a hammer bit to be tested under controlled conditions in a known rock sample. The test fixture is described in greater detail in Appendix H.

Figure 6. Sandia percussive hammer test rig.

The bits were predominantly tested in Sierra White Granite (28.2 ksi compressive strength) for the bit parametric testing. A typical test consisted of setting the regulator pressure on the bottle farm, and then driving the bit into the rock at one to three WOB (weight on bit) values per hammer pressure (if possible, depending upon the ROP achieved and the drilling length available). The reactive torque was monitored during the drilling. The rate of penetration was determined from the change in block height over time. Most of the bits were tested up to approximately 1,500 psi hammer input pressures. Generally the speed was increased with pressure to maintain a uniform number of blows per revolution.

5.2.2 Conventional Hammer and Bit Test Results

Representative results of the bit parameter variation testing on Numa P35 hammers are shown in the following figures. Figure 7 shows the test-measured ROP increases according to the prediction from the thermodynamic model until the actual penetration rate falls off with increasing pressure in the vicinity of 1,000 psi. Figure 8 demonstrates the majority of the power delivered to the rock resides in the percussive component, whereas the rotary contribution reaches a stable value with increasing pressure. Figure 9 demonstrates that the hammer is operating near the specific energy of the granitic rock sample, which has a compressive strength of 28,200 psi unconfined compressive strength (UCS).

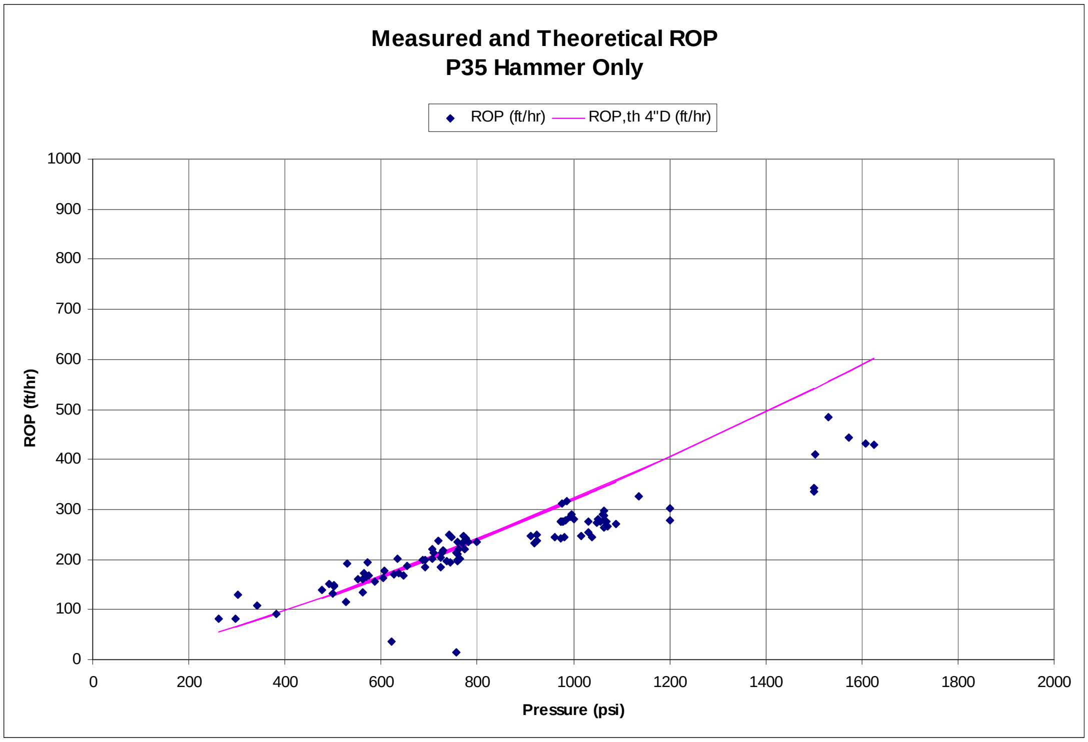


Figure 7. Measured and predicted ROP (based on P35 hammer power) for drilling Sierra White Granite with a 4-inch-diameter bit on a P35 Numa hammer.

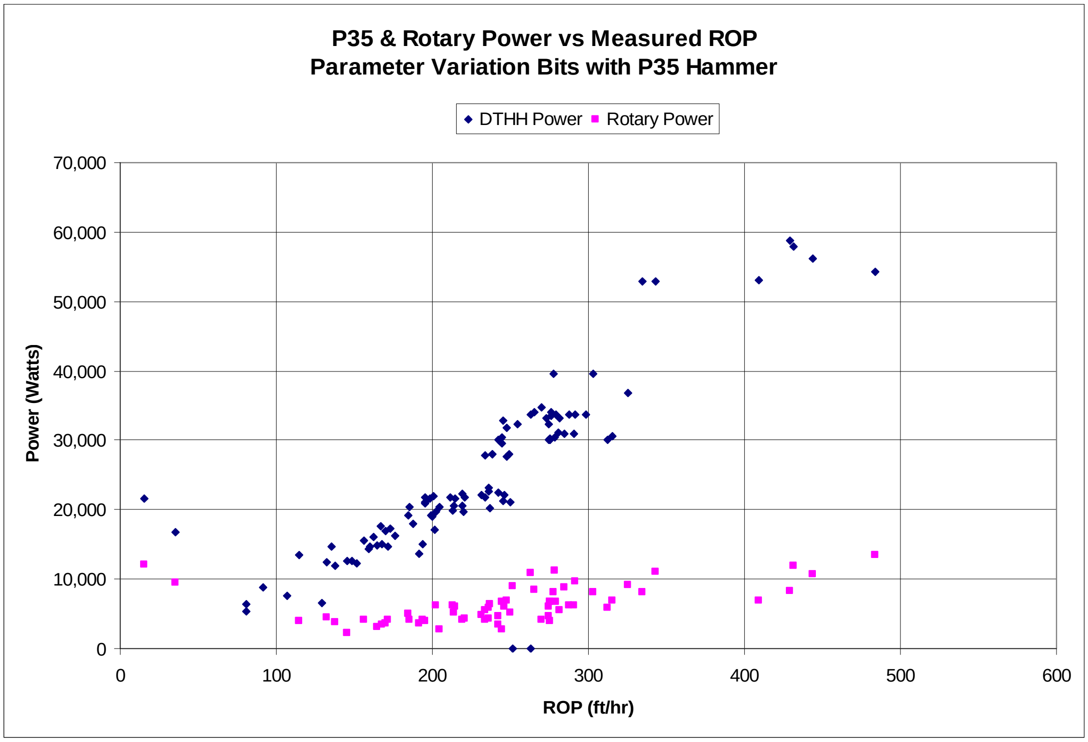


Figure 8. Power versus ROP for the data in Figure 7.

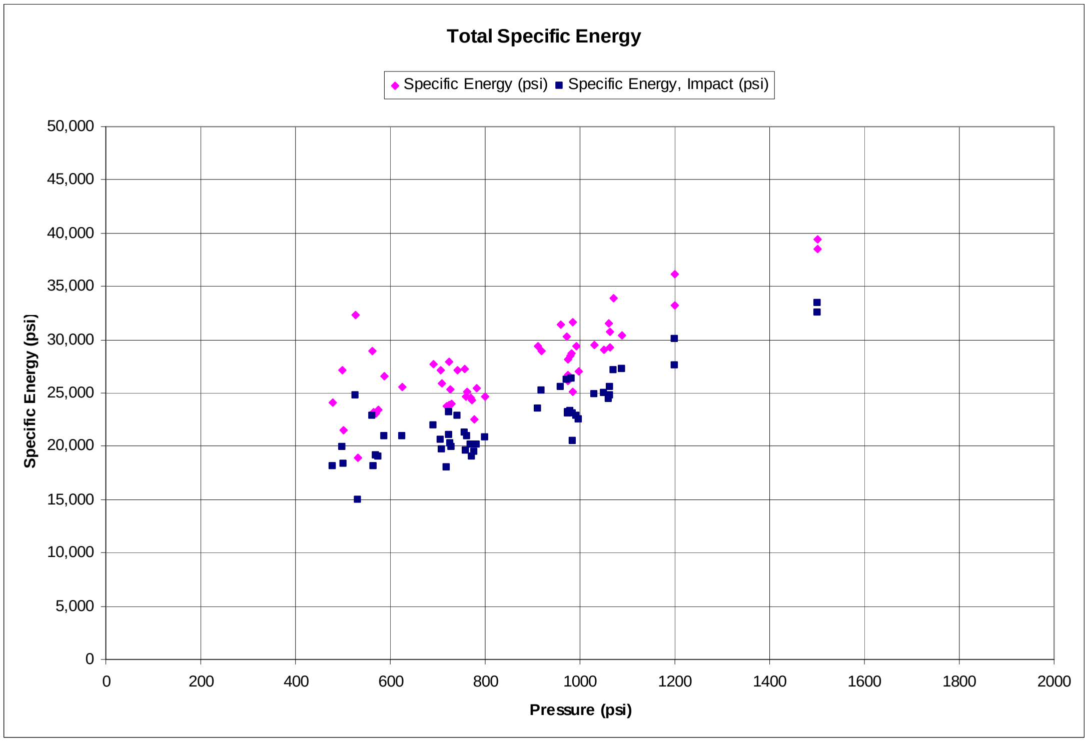


Figure 9. Specific energy (total and impact) for the data in Figure 7.

5.3 High-Performance Hammer and Bit Development

The thermodynamic model was used to evaluate the ROP performance of the P35 hammer diminishing around 1,000 psi. Various regions in the hammer experienced choked flow. Additionally, the conventional bit was providing significant back-pressure on the hammer assembly due to its inability to move the required volume of flow and rock cuttings through the junk slots on the bit at higher penetration rates. This performance limitation was addressed by developing a second-generation series of bit parameter variations and testing them on high-performance hammers (“S35S”) that were developed based upon performance optimization of the hammer cycle using the thermodynamic model. Results from these developments are shown in Figure 10 for a 4-inch-diameter bit on the high-performance hammer. The performance envelope follows the theoretical prediction beyond the previous limitation of 1000 psi. This process was repeated for 3.75-inch-diameter bits, as shown in Figure 11. Penetration rates in excess of 800 ft/hr have been observed. These penetration-rate performance enhancements are unprecedented for drilling in granite.

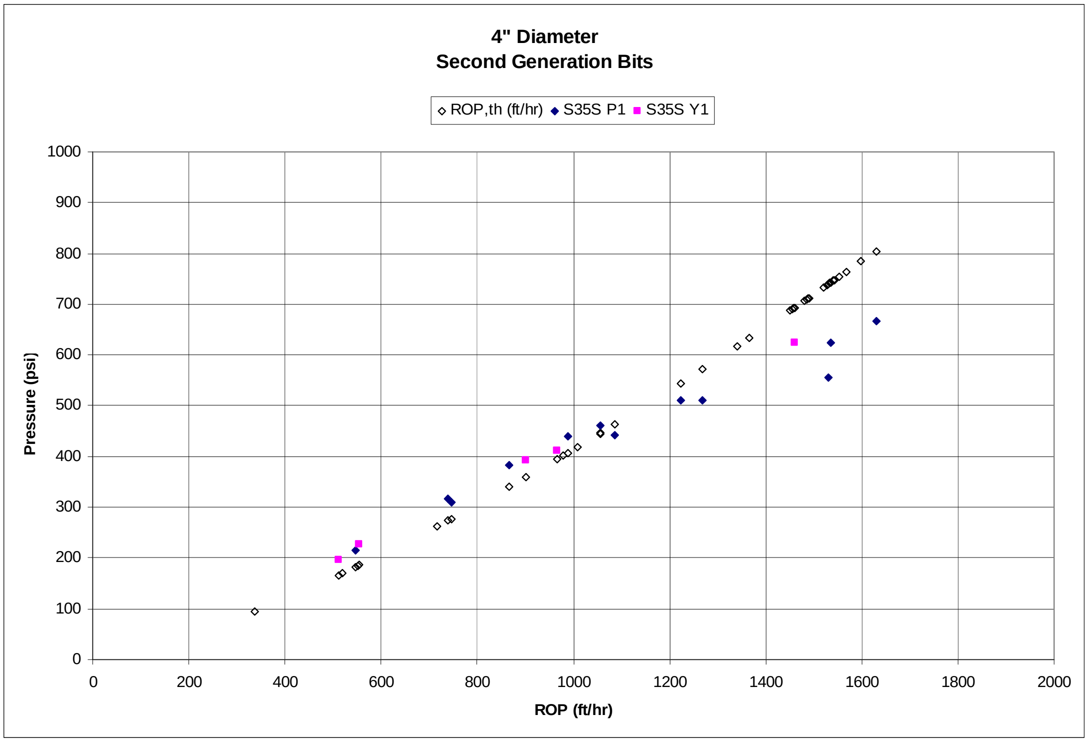


Figure 10. ROP versus pressure for drilling Sierra White Granite with second-generation 4-inch-diameter bits on high-performance hammers (S35S)

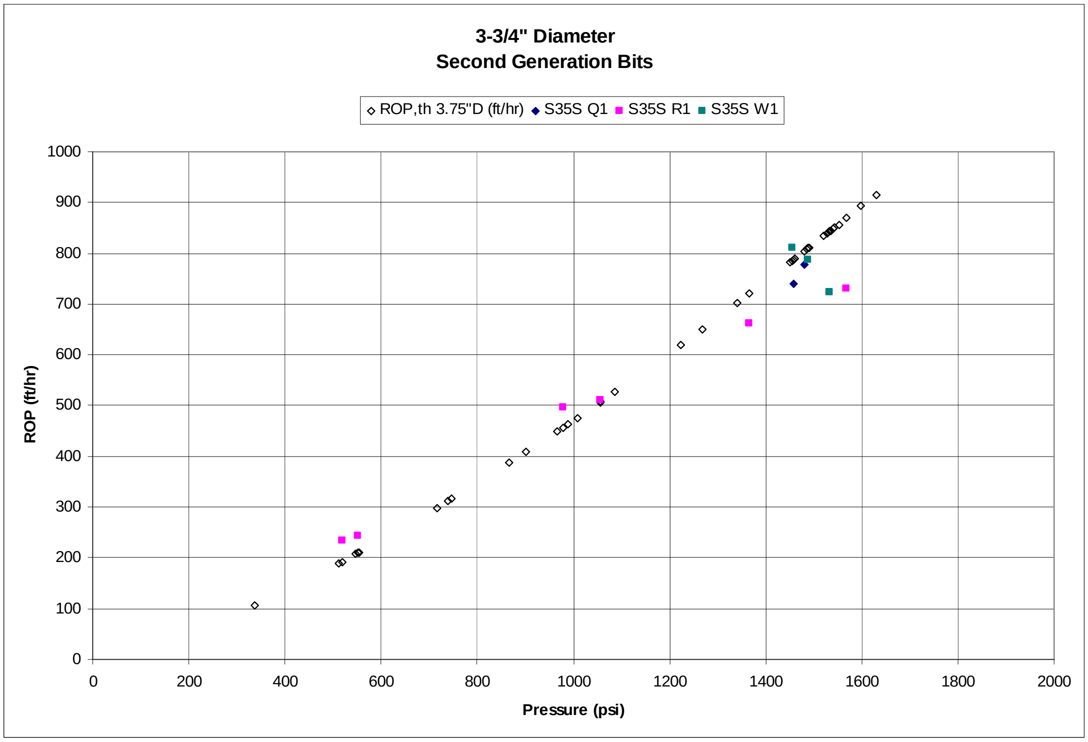


Figure 11. ROP versus pressure for drilling Sierra White Granite with second-generation 3.75-inch-diameter bits on high-performance hammers (S35S).

5.4 Development and Testing of the 5-inch Hammer

As outlined in the requirements, NIOSH has indicated a larger diameter wellbore would be compatible with fielding various downhole communications tools. Hence, the test procedure and performance enhancements described above were applied to a 5-inch-diameter Numa hammer (P35), and thermodynamic model optimized hammer (SP50) with larger bits(5-1/2 and 6-inch-diameter).

The raw data for ROP versus pressure in drilling granite is plotted in Figure 12. Set points for the tests were 350 psi, 525 psi, 700 psi, and 1,000 psi. The general trend for the data shows an increase in ROP with increasing pressure. However, there is a drop in the ROP from 700 psi to 1000 psi for both the stock P50 and the SP50 hammers. For both hammers, there is significant scatter in the data at all operating pressures. Significantly less work has been done on the larger diameter hammers to date than the smaller diameter hammers reported on above; hence statistical methods are used to evaluate the data.

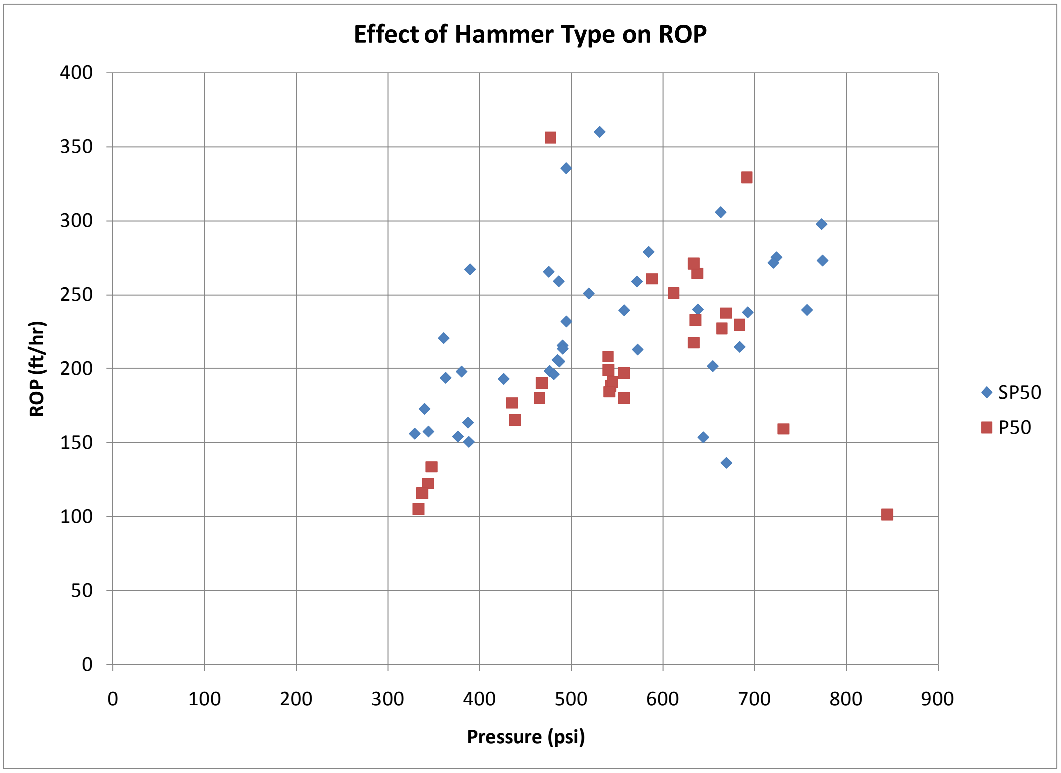


Figure 12. Raw data for drilling granite blocks with P50 versus SP50.

In order to quantify the data, an analysis of variance (ANOVA) was performed to evaluate the significance of the variation between the test results. The data were treated as having two factors (pressure and hammer) and one response variable (ROP). A main effects plot of the input factors is shown in Figure 13. The horizontal line around 197 ft/hr shows the overall average ROP for the tests. The average ROP for the P50 and SP50 are shown on the left side of the figure. The average ROP for each of the pressure settings is shown on the right side of the figure. The ANOVA indicates that the pressure is a significant factor while the hammer has less influence.

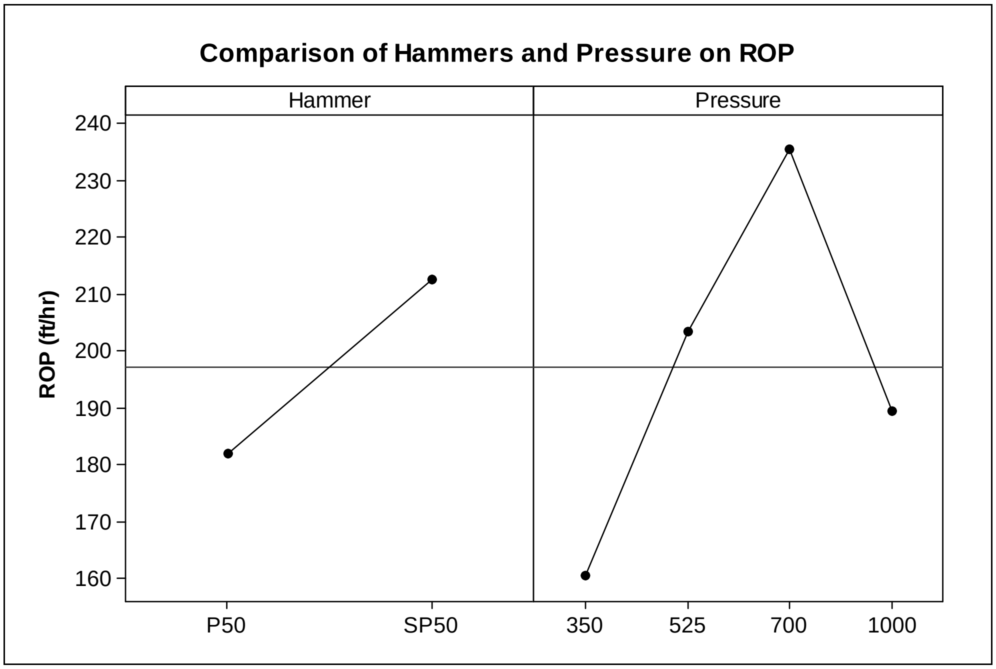


Figure 13. Main-effects plot of hammer and pressure for 5-inch hammers.

A similar comparison was made for the effect of the bit diameter on the ROP. The SP50 hammer was operated with both a 5.5-inch-diameter bit and a 6.0-inch-diameter bit. The raw data for the ROP measurements are shown in Figure 14. A visual evaluation of the data shows an increasing trend in ROP for both hammers. However, as in the previous set of data, there is significant scatter in the data.

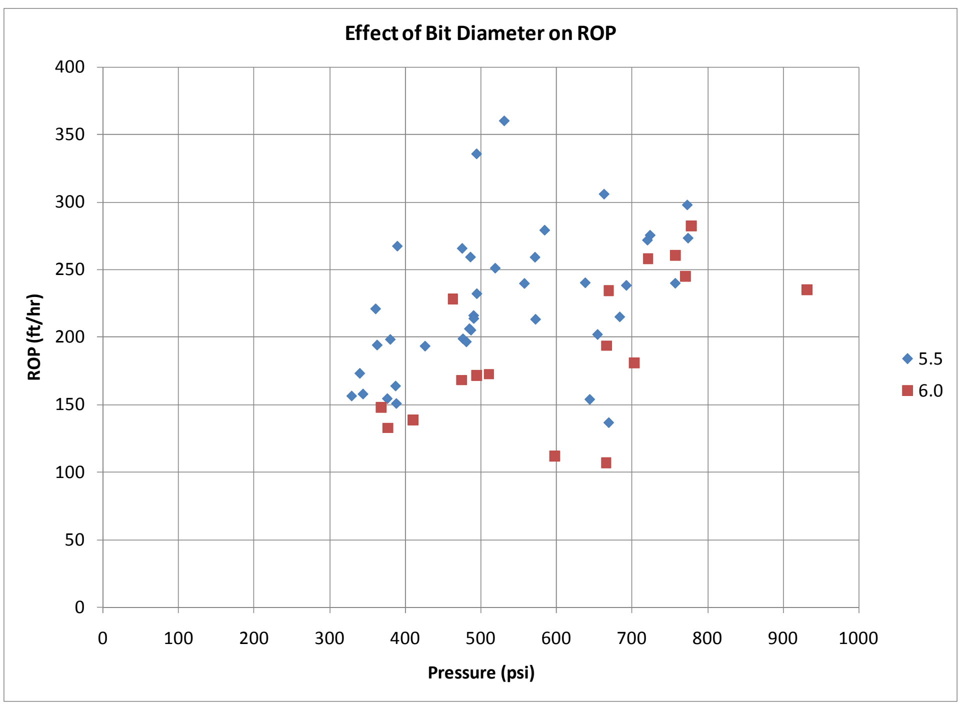


Figure 14. Raw data for 5.5 and 6.0-inch-diameter bits.

An ANOVA was performed on the data to evaluate the effect of bit diameter. In this analysis, the input factor is the bit diameter while the response variable is the ROP. The average ROP for all of the test runs was around 216 ft/hr. The average ROP for the 5.5-inch bit was around 244 ft/hr while the average ROP for the 6.0-inch bit was around 189 ft/hr. The main effects plot of the bit diameters is provided in Figure 15.

The ANOVA results in a P-value for the hammer diameter of 0.001. This indicates that there is a statistical difference between the ROP for the two bit sizes.

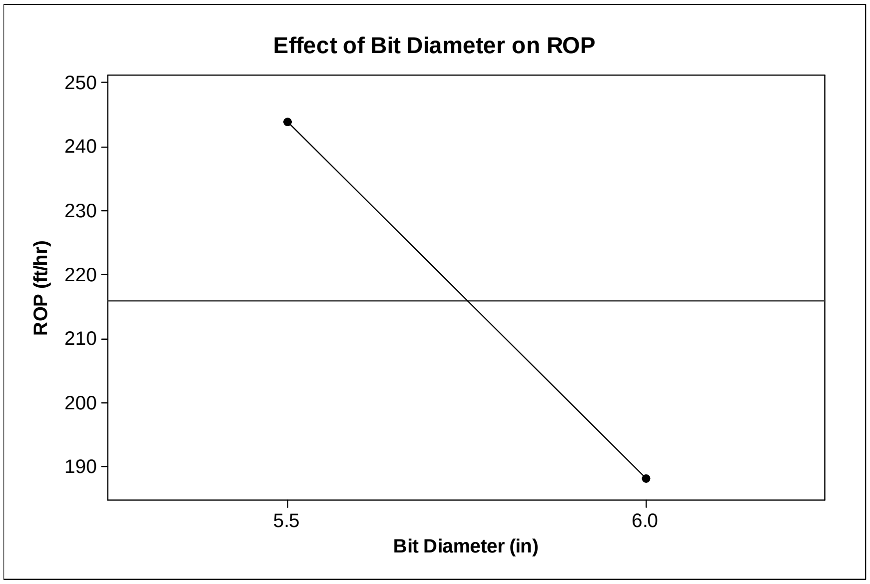


Figure 15. Main effects plot of hammer and pressure for 5-inch hammers.

Typically, the ROP is inversely proportional to the square of the diameter of the bit, as shown by the following equation.

$$ROP \propto \frac{1}{d^2}$$

In this case, the 6.0-inch bit is approximately 10% larger in diameter than the 5.5-inch bit. This translates into a 20% larger area which means that one would expect the ROP to be approximately 80% of that of the 5.5-inch bit.

For the data that were collected, this relationship holds true. The average ROP for the 5.5-inch bit is around 244 ft/hr while the average ROP for the 6.0-inch bit is around 189 ft/hr. The results show that the ROP for the 6.0-inch bit is around 77% of the ROP found in the 5.5-inch bit.

5.5 NIOSH Rock Sample Test Results

To evaluate the range of rock types that may be encountered in an MRDS application, NIOSH provided several rock samples that are representative of typical mine geologies that may be encountered. These rock samples and their lab-tested nominal compressive strengths include the following:

- Buckskin Sandstone 10,945 psi UCS,
- Sedona Red Sandstone 15,770 psi UCS, and
- Arizona Sandstone 20,580 psi UCS

Some of the foregoing hammers (P35) and bits were tested in these rock samples. The results are presented below. For comparison, the results from the 525 psi set point are highlighted in the figure (Figure 16). The data show that the ROP varies with material type. Generally, the lower UCS materials did result in higher ROP.

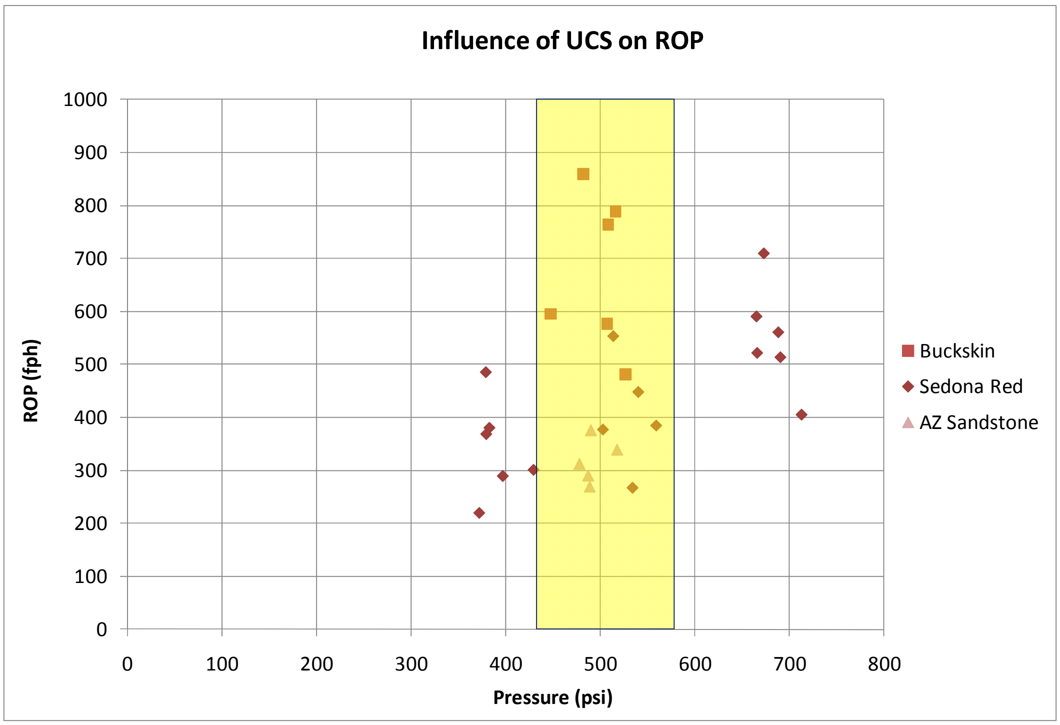


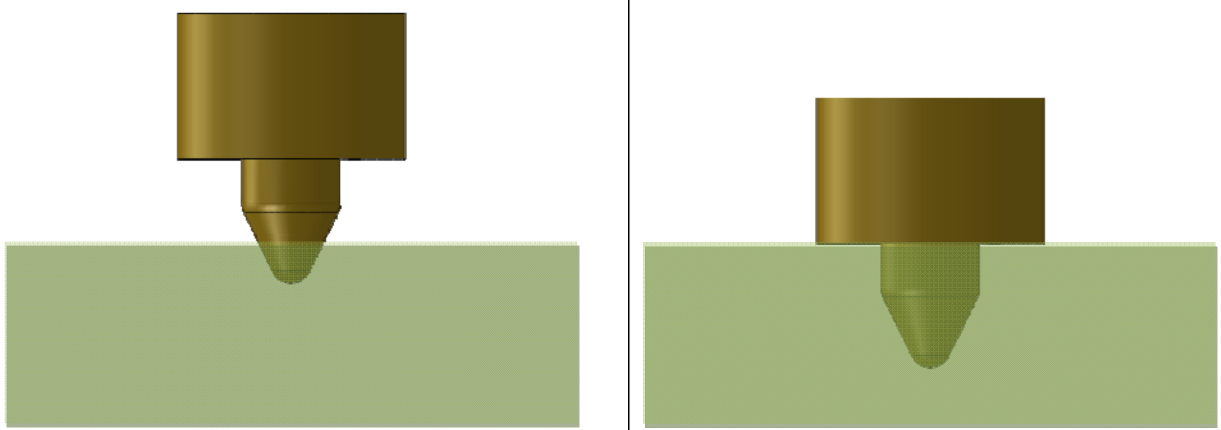
Figure 16. Influence of UCS on ROP.

The thermodynamic model was used to predict the ROP for each of the materials based on the UCS and the operating pressure. The results from the model are listed in Table 1. The predicted results follow conventional wisdom that ROP is inversely proportional to the UCS of the material.

Table 1. Predicted versus Measured ROP at 525 psi

Material	UCS (psi)	Predicted ROP (ft/hr)	Average ROP (ft/hr)
Buckskin Sandstone	10945	300	677
Sedona Red Sandstone	15770	210	383
Arizona Sandstone	20580	160	316

A noticeable discrepancy exists between the predicted and the observed behavior in Sandstone—presumably due to the Sandstone being a less brittle rock. Fortuitously, significantly greater rates of penetration are observed than would be expected from the percussive energy alone. This is partly due to the fact that for high-compressive-strength materials like Sierra White Granite, the energy delivered by the hammer is used more efficiently. In hard tock, the button penetration is limited to the cutting face of the button and the hammer operating near the specific energy of the rock. This is illustrated on the left side of Figure 17.



Proper button contact | Buried button

Figure 17. Depth of button penetration.

If the power delivered to the material exceeds the specific energy required (a likely scenario for lower UCS materials), then the buttons will become buried in the material. When the bit bottoms out, the extra penetration causes an increase in contact area between the bit and the rock. This is illustrated in the right side of Figure 17.

As shown in Figure 8 presented previously, the rotary power also contributes to breaking rock. The penetration rates observed in Table 1 exceed what would be expected for the percussive contribution alone. In softer rocks, percussive drilling technology is effective even though the bit may perform more like a drag bit when drilling these formations.

6 Conceptual System Design and Specification

A preliminary approach has been conceived for the conceptual system design of the MRDS consisting of three primary system components. First, the basic MRDS relies on having a local drilling contractor respond to the site to provide the basic drilling infrastructure needed to employ the MRDS BHA. The mine operator in conjunction with command-center personnel reviews key information such as current mine maps, reports from on-shift crews, and survey data. Then the mine operator and personnel from the command center establish the drill location and allow the drilling contractor to spud the hole and commence drilling. Because of the shallow depth, the majority of the mines in the Appalachian region may only need conventional hammer drilling to develop the initial probe hole—which was the case in the Quecreek entrapment.

However, as presented in previous sections, higher-speed drilling systems may be required under certain conditions. Hence, the second part of the conceptual design consists of deployment of an enhanced capability to handle deeper or more difficult drilling conditions. This system consists of the higher-speed enhanced DTHH (down-the-hole hammer) drilling system. This two-part approach forms the basis for the NIOSH MRDS conceptual system design as illustrated in Figure 18.

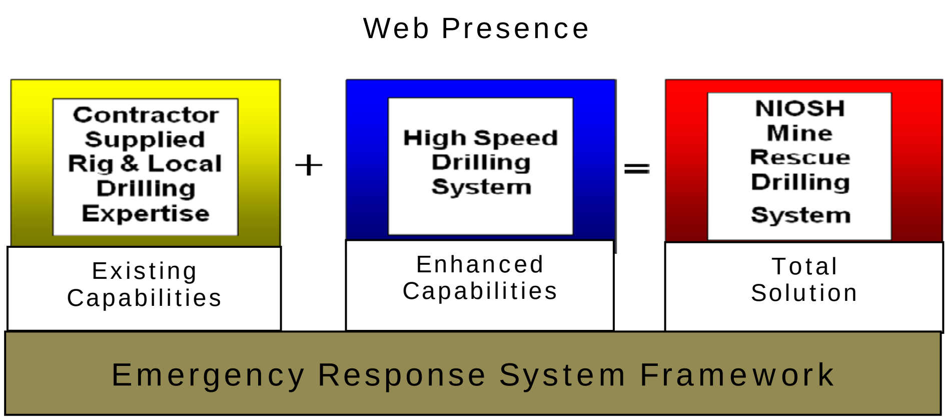


Figure 18. Advanced hardware deployment solution.

The third component of the system is an internet presence (web site) that allows the MRDS to be rapidly deployed, facilitates necessary communications, and coordinates pre-event planning. The objective is, during a mine entrapment, to improve the logistical response for emergency response personnel to respond to a mine entrapment. A web site is currently an effective way to achieve this objective. There are other plans that can be made to improve the logistical response.

The advantages of this overall approach to an MRDS include the following:

- Minimize hardware maintenance to NIOSH/MSHA
- Reduce transportation requirements
- Improve system readiness
- Rely upon local drilling expertise
- Enhance versatility and functionality

Each of the components of the overall concept design is discussed below.

6.1 Existing Commercial Capability

The local drilling contractor provides the basic infrastructure to support the MRDS. There are several motivations for relying upon this capability. The drilling contractors

- are experienced with the regional drilling conditions,
- can be onsite quickly,
- understand the regional geology, and
- have established relationships with local equipment suppliers that can be leveraged to secure support equipment

To ensure timely response in an emergency drilling situation, the drilling contractor should ideally be known by the mining company as a provider of foundational drilling services with the capability to supply men and equipment that can be integrated with and will support operation of the enhanced high-speed drilling BHA. Local drilling contractors would have access to web information on the requirements and fixtures needed to use the MRDS BHA system and thus make sure they are prepared before arriving at the site. For example, to use the envisioned high-performance percussive hammer, they must additionally have drilling equipment capable of injecting air through the swivel at 1,500 psi. To begin operations and probe hole development quickly, the drilling contractor must have access to mine data and be familiar with the local drilling conditions. The federal and state agencies working with the mine personnel (command center) will establish the framework and operational plan to initiate probe drilling.

6.2 Deployment of Enhanced Drilling Capabilities

In a shallow entrapment, the time to transport an advanced BHA may be greater than the time for the first-response driller to mobilize and penetrate the mine using conventional technology. However, this may not always be the case. Depending upon the depth of the entrapment and the severity of the drilling conditions, the foundational capability provided by the drilling contractor may need to be augmented with high-speed drilling components to decrease the drilling time to rescue. The high-speed drilling system includes downhole components (BHA), and additional surface equipment such as compressors and boosters. In future versions, the system may include an entire compact drill rig. These components will be added to the drilling process as they are made available to the drilling contractor onsite. Under this scenario, the additional hardware and surface support equipment is progressively deployed as the need arises to augment the drilling process. Ultimately, in the event of a deep entrapment or one requiring specialized mine rescue drilling hardware, the drilling contractor would need to take additional steps to integrate his rig with the specialized equipment (such as casing advancement systems). This enhanced capability may include hardware (BHA, surface equipment, drilling diagnostics with drilling advisory systems, communications, and various other components). Some equipment may require that personnel with special training in its use be onsite to assist in the operations.

The first deployable system hardware to be available for immediate mobilization under this configuration would be a high-performance hammer system, as described previously. This initial configuration relies upon contractor rigs to deploy these systems. Interfaces will be specified to meet “standard” drill rig configurations predominant in practice (Ingersoll Rand/RD20, Atlas Copco/T4, Schramm, and others) to ensure breadth of compatibility.

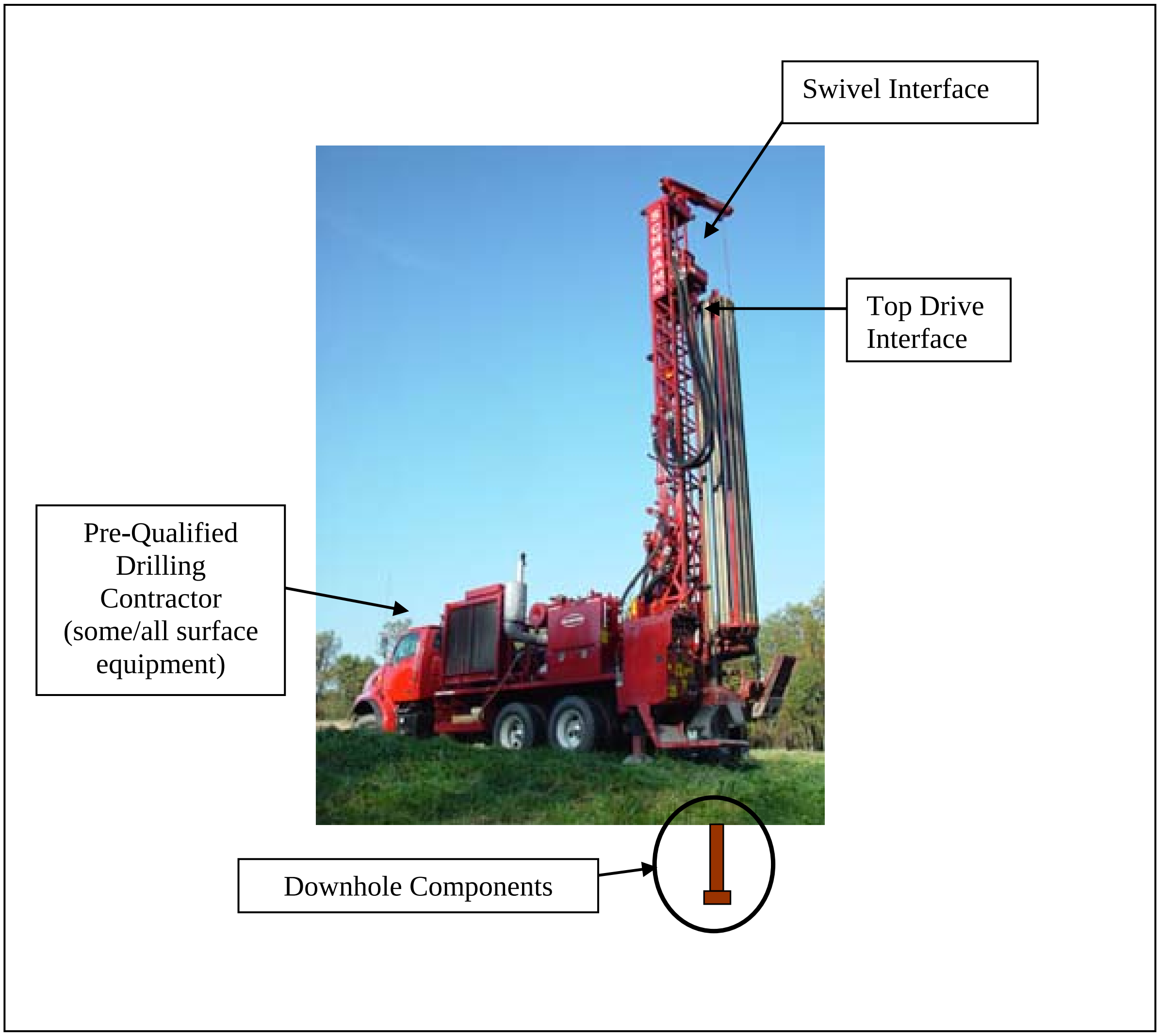


Figure 19. Local contractor providing foundational drilling capabilities with well-defined interfaces to enhanced drilling capability requirements (Photo courtesy of Schramm)

The major system elements that comprise this enhanced capability are listed below and illustrated in Figure 19. These components can be progressively mobilized and connected to the system to improve the drilling rate.

- Well-defined interfaces
- Downhole components
- Surface equipment
- Drilling measurement system
- Drilling advisory system
- Satellite uplink

- Communication Systems.

These are addressed in the following subsections.

6.2.1 Well-Defined Interfaces

To be used by the local drilling contractor who has more than likely never seen the hardware, the high-performance BHA will need to have well-defined industry-standard interfaces that are compatible with the rig that is deployed onsite. As depicted in Figure 19, the primary interfaces are (1) on the swivel, to ensure the equipment is rated for the high-pressure air stream required by the down hole hammer; (2) below the top drive where the drilling diagnostics sub would connect to monitor the drilling conditions on the rig; and (3) on the drill string where the BHA connects to the drill string.

6.2.2 Bottom Hole Assembly (BHA) Component Toolbox

Rather than a single solution, a toolbox of components could be maintained that allowed the preferred BHA configuration, as depicted in Figure 20, to be deployed for a given drilling condition. MSHA's maintenance and deployment of their rescue capsule is an analog for how a BHA could be similarly handled. It is envisioned that percussive hammers will be able to penetrate the majority of formations that are anticipated for this application. However, there may be problematic formations (water saturated mudstones, clays) where other solutions may be desired. The toolbox approach allows a variety of solutions to be considered and would likely include the following.

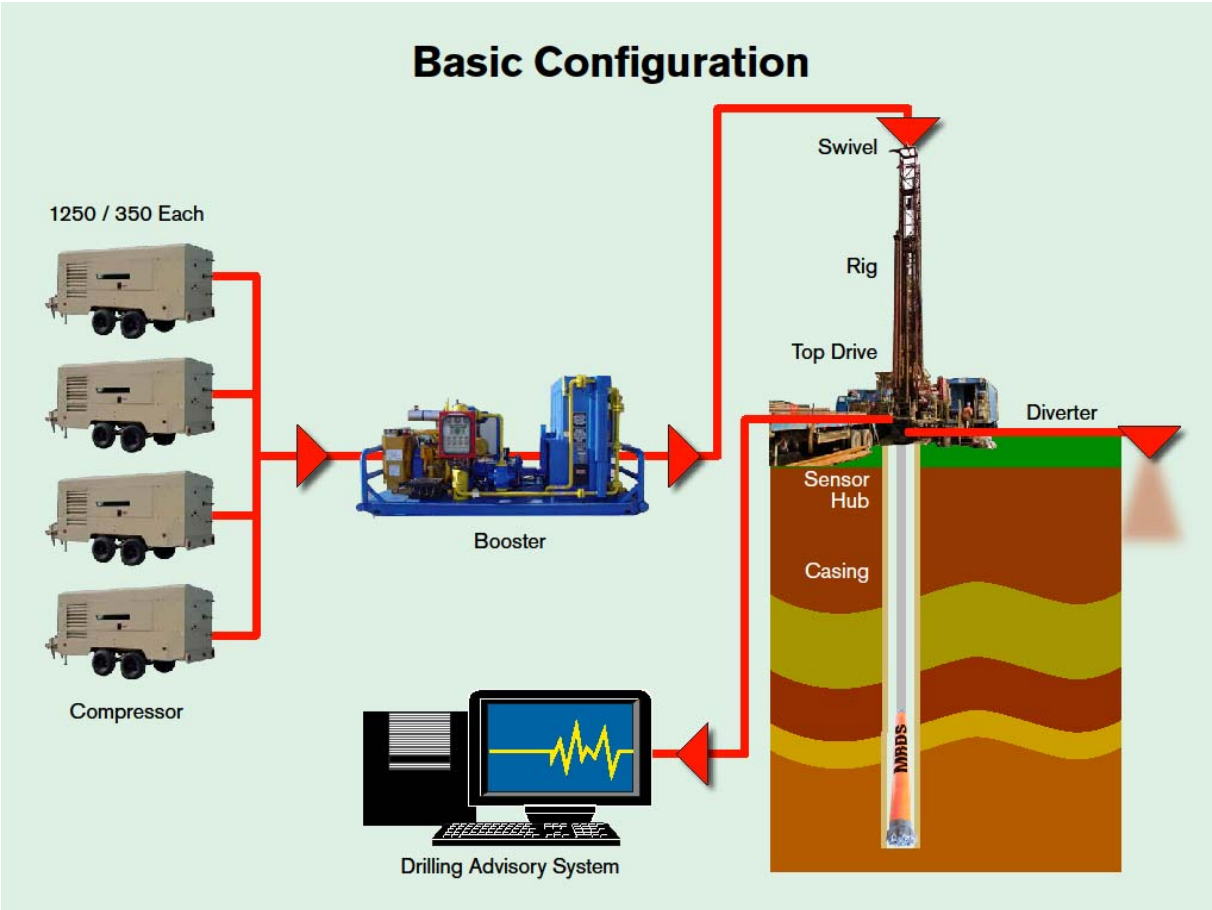


Figure 20. Basic configuration of the percussive hammer solution for the MRDS (Booster photo courtesy of Keystone Drill).

High-Performance Percussive Hammers

High-performance hammers, as described previously, form the basis of the enhanced capabilities that can be deployed to the drill site to expedite the drilling process.

Casing Advancement Systems

As noted, percussive hammers can be complemented by casing advancement systems that allow concurrent casing placement while drilling the overburden. Although not compatible with the high-performance percussive hammers referenced above, they are compatible with many commercial off-the-shelf (COTS) hammer systems routinely used by many drillers. A percussive hammer equipped with a casing-advancement-type bit could be transported to the site to assist drilling the overburden and setting casing in preparation for subsequent drilling activities.

High-Performance Rotary Drilling Systems

As noted, PDC bits have improved in recent years and are able to successfully penetrate medium-hard formations. Although these bits have limitations of self-induced vibrations when drilling at greater depths, this should not be an issue for the MRDS depth applications. Downhole motors, positive displacement motors (PDMs) and mud turbine with PDC bits and/or impregnated diamond bits offer a convenient solution to drilling the softer formations that a percussive hammer does not handle well. However, downhole motors are typically very lengthy and not amenable to easy transportation.

Directional Drilling Solutions

Along with high-performance hammer development, companion work is under way to evaluate the effectiveness of directional drilling capabilities with percussive drilling systems. Following the traditional method of rotary drilling, a bent sub can be used to allow the hammer to build angle. Where PDMs (Moineau) are used, adjustable bend housings (ABHs) are sometimes integrated into the overall design of these tools. Although rotary-steerable systems are not envisioned as a standard component of the BHA toolbox, they offer fairly aggressive build rates.

6.2.3 Surface Equipment Augmentation

Compressors

Most air rotary rigs are equipped with onboard compressors. However, high-performance percussive hammers are able to drill faster because more power is delivered to the rock face. Accordingly, additional fluid power must be developed at the surface and conveyed down the drill string to the hammer. Although a later phase of this project could seek to develop advanced, compact gas compression delivery systems, for the present this equipment would be limited to conventional rotary screw type compressors. These units, however, are routinely packaged on structural steel skids and airlifted into conventional drilling operations

Booster

A booster is used to add additional energy to the air stream by increasing the gas pressure. Like compressors, they are self-contained packaged units that are routinely used for production drilling operations. Conventional percussive hammers operate at the output pressure of standard compressors. A booster is used when excess pressure is needed to overcome fluids in the wellbore or lift cuttings to the surface from greater depths. A booster is needed as part of the baseline configuration of the high-performance MRDS to increase the power delivery to the hammer.

Nitrogen Production Unit

In the presence of a potentially explosive atmosphere in a coal mine rescue situation, an NPU allows the system to be run at a higher operating pressure than would be possible with air alone. Likewise, NPUs are routinely used for production drilling operations to reduce the likelihood of a wellbore gas detonation when using percussive drilling for hydrocarbon wellbore construction. They also are packaged on skids for routine airlifting around the globe. Some NPU service providers have expressed a keen interest in providing nitrogen services if needed for a mine rescue drilling operation.

Whether nitrogen is used initially in a gaseous or liquid phase, there is concern of post mine penetration effects. If miners are trapped in a relatively small confined space (a likely scenario), MRDS penetration using nitrogen-rich gas could raise levels of nitrogen high enough to create a life threatening, oxygen deficient environment. To avoid this scenario, drillers could slow down drill speed just before mine penetration and switch the MRDS over to compressed air. A slower drilling speed would lower required air pressures, thus mitigating the risk of detonation caused by high air pressure in the presence of a fuel source.

Mist / Lubricant Injection System

Some drilling conditions will require a mist be injected into the circulated fluid to stabilize the wellbore. It can also facilitate cuttings transport and reduce the atomization of the cuttings in the vicinity of rig operations. This piece of equipment is often standard with percussive drilling systems.

Not all of this equipment need be in standby. Various suppliers, both regional and national, can be relied upon to provide this equipment in the event of an emergency through pre-established supplier agreements. By having well-specified equipment requirements, as is facilitated through this study, the list of necessary suppliers for this type of equipment can be reduced.

6.2.4 Drilling Diagnostics Instrumented Sub

In order for the drilling contractor to achieve the preferred response from a drilling system where he may have had little experience, it is worthwhile to standardize the interface to the drill rig so that drilling measurements can be made to monitor the response of the overall drilling process. The drilling diagnostics sub proposed here is a single sub that connects to the top drive of the contractor rig and makes the majority of the measurements necessary to the successful operation of the high-performance BHA. This sub would be equipped with multiple sensors to allow the overall drilling process to be quickly instrumented. It would take the place of the more conventional instrumentation that is typically used on a rig to monitor the drilling process. The advantage of this approach is a single piece of hardware to collect a variety of measurements. Some of the measurements this system would monitor include drill-string rotary speed, weight on bit, torque on bit, fluid pressure and flow rate, and top-drive head height. Although all measurements may not be able to reside in a single sub, the majority of measurements vital to monitor the drilling performance of the high-performance percussive hammer presumably could. The conceptual design for this subsystem is described in greater detail in Appendix F.

6.2.5 Drilling Advisory Subsystem

This is a data acquisition and display system that is specifically developed to complement the high-performance hammer systems that would more than likely be deployed. It relies upon a single interface, the drilling diagnostics sub described above, to gather operating conditions and drilling performance data during the operation. It processes and displays the information in meaningful formats to be interpreted by the driller. It can also be configured to port this information to the Internet where a drilling engineer can review the data to make recommendations on improving the drilling performance in support of the rescue drilling effort. A high-level description of the equipment and what it does is provided in greater detail in Appendix F.

6.2.6 Communication Systems

Although not specifically identified here, the toolbox could potentially include rig site communications systems to facilitate efficient communications on the rig site.

6.2.7 Other

Although never used, the Quecreek mine rescue operation addressed the possible need for an airlock as part of the miner rescue operation. There may be other specialized hardware technologies that should be addressed as part of a total solution to mine rescue technology. An air lock is just one such example.

6.2.8 Fit-for-Purpose Mine Rescue Drill Rig

As drilling technology continues to advance, it is possible that in the future it may prove worthwhile to have a surface drilling unit that can interface with the requisite functionality of the entire high-speed-drilling concept to optimize performance in a way that a local contractor rig cannot. Such a fit-for-purpose mine rescue drill rig could be, for example, a CTU that is specially designed to be compatible with high-performance percussive hammers. The advantage of a coiled tubing unit is that it allows continuous injection of the drill pipe, thereby accommodating higher overall drilling rates. Although it may take longer to mobilize this unit to the site, this system could be used to penetrate to greater depths more quickly. As part of research on the heretofore-mentioned leveraged program, Sandia is evaluating the effectiveness of coiled tubing technology for this application.

Furthermore, the fit-for-purpose rig could be used for training as a part of an ongoing mine-rescue training program. This would also serve to increase awareness of the overall MRDS system capabilities for when it is actually put into practice in an event. Although such a system would not be compatible with the current desire to minimize up-front development cost and effort and to minimize maintenance and storage costs, advances in the future may lead to the desirability of such integrated systems.

6.3 Internet Presence

The logistical solution recommended by Sandia for mine accident response includes more centralized and more readily available communication through an MSHA web site and adding information modules, related to drilling, to the existing mine rescue program structure. MSHA already has protocols for accident response that would form the foundation structure for the web site. The added value from the instant, centralized communication available through an access-controlled Internet site is obvious. It will also allow multiple communications to one place at the same time, a site that can be viewed by all in the command center, and it will archive the communications and their timing for more effective postaccident analysis. This should add value by relieving some of the communications-related time demands on those in the command center. The introduction of rapid drilling for underground condition assessment and rescue support will require that drillers become familiar with the new technology if it is to be maximally effective. The second element of logistical solutions is to improve accident response related to drilling by using the web site and by informing potential drilling contractor staff about the special requirements of accident response and rapid drilling.

Sandia research has found that in the past, mine rescue drilling technology was developed and set up on standby but became unusable because it fell into disrepair and because it did not become a well-recognized element of the accident response protocol. Sandia envisions simpler drilling-technology solutions, information, and specifications aimed at informing the drilling industry and blending the use of this technology into the accident response protocol as a means to mitigate the prior negative outcomes. The web site is a key element in creating familiarity with the equipment within industry, informing people when training is available and in blending MRDS technology into the accident response protocol favored by MSHA.

Once a web site is established (most likely under MSHA), it could act as a centralized logistics and communication tool for mine accident response. For this study, Sandia developed a broad-brush outline for a web site that is introduced in Appendix K. As part of the MRDS development effort, Sandia could work with MSHA or other agencies to develop a more focused prototype web site. The four mine accidents, with their rescue responses, summarized in Appendix C illustrate the complexity of assessing, responding, mobilizing, developing strategies, and executing strategies when time saved means lives saved. Communication is the foundation for all actions in a mine rescue response, and today the Internet allows more efficient, centralized communication for all, including those marshalling assets distributed widely across the United States. For this tool to be effective, it must be carefully structured, tested, cyber-secure, maintained and "socialized" with the potential users with repeated reinforcement of that socialization. The tool will be successful in direct proportion to the support efforts that follow its establishment. It is expected that socializing this tool and developing a robust, ongoing support structure will take some time. It is also understood that there could be a time when the system is "down" or unavailable to key people due to unforeseeable circumstances, so there should be redundancy through retaining non-Internet protocols and lines of communication for backup.

It is envisioned that the web site would be a place to post and constantly update information describing the initial and evolving accident situation and to post basic data such as area maps, the geologic section for the mine, and the technical specifications and operators manual for rescue equipment like the MSHA mine rescue capsule and the Sandia proposed MRDS. Knowledge of past information needs and proposed rescue technology would be the basis for structuring the "Site Data and Rescue Response Baseline" area of the web site. Again, this would require input from MSHA for structuring the data-requirements bins. Rescue response related to drilling will be used as an example of a rescue element that could benefit from information populating this part of the web site.

The envisioned web site could be used to post basic information that could be useful to all responders, including map location of the mine and the best routes to travel with heavy equipment, terrain at the site, accident area at the mine (GPS coordinates when available), supposed accident conditions, conditions related to safety hazards (above and below ground) caused by the accident, current weather conditions if they affect access or vehicles needed, and roles/responsibilities/contact information for the onsite mine operator, MSHA and other key personnel. Site-specific information required by drilling contractors includes a geologic section with hydrology, formation thickness and depths, any known conditions that would affect drilling (like clays), and mine depths and workings layout. Drilling contractors and MRDS deployment support can use the web site to communicate their questions and particular drill-site setup needs while the equipment is being mobilized. This would allow tailoring the "tool box" deployed to be maximally effective given the drilling conditions. For example, wet, clayey sections may require a different bit than drier sections with low clay content.

The web site can be used as a standing source of information regarding emergency response resources available. National, regional, and state resources can be described along with contact information and protocols for their response. With regard to the MRDS, the information would include a tool box inventory with recommended applications for the equipment (decision tree for applications), equipment specifications and information on interfacing with other standard drilling equipment (for BHAs), operator's manual(s), standby location, roles/responsibilities/ contact information for those who deploy the equipment, mobilization requirements (shipping specifications, type of transport that can be used), onsite support requirements (electrical, fuel, etc.), and a list of contractors and locations with crews who have had training on specialized equipment. If military transport is used, the web site can be used as a coordination tool among the many entities involved and as a means to convey basic site information to transport personnel (helicopter). A BHA specialized to support rapid drilling can be developed to relay data back to a web site via satellite in real time. This capability could convey drilling depths and underground conditions.

The MRDS section of the web site is the interface for the MRDS to the world. It is intended to provide a unified and consistent interface for most users to the system. More detailed information on the conceptual design and functionality of the proposed MRDS area of the web site can be found in Appendix K.

7 Concept of Operations

7.1 Overview

The MRDS is envisioned as a nationally available asset of which there will be multiple units, standing by at diverse geographic locations, possibly four. The purpose of this section is to lay out a conceptual sequence of events and activities that portray the potential life cycle of the MRDS. We call this a concept of operations or CONOPS. A CONOPS lays out the cycle of events that would be involved in the use of the MRDS in a mine rescue operation. This information ties together the system components and the interfaces with other systems and activities that will play a role in the deployment, such as storage, transportation, and maintenance. The first deployed MRDS will likely be in the “Tool Box” form with the basic BHA (bottom hole assembly) and additional supporting equipment and fixtures. Developing a CONOPS supports the design process by making sure the system is designed to accomplish all the needed functions and that the designers account for all the possible interfaces with other systems.

7.2 Basic CONOPS Script

The CONOPS for MRDS consists of the following basic steps that are further illustrated in Figure 21:

1. Equipment/Storage: Equipment is in designated storage locations and maintained in a ready/standby mode.

2. Event Occurrence and Reporting: An event is reported and assessed through existing mine emergency procedures and channels. A decision is made that drilling may be part of the location/rescue.

3. Deployment: The MRDS tool box is readied, and arrangements are made to ship to site via the most expeditious mode. The drilling contractor is notified and prepares to deploy to the site. The support equipment list needed for the MRDS (compressors, boosters, etc.) is activated and arrangements are made to deliver.

4. Rig-Up and Checkout: Drilling locations are specified, facilities are modified to get equipment to the drilling locations (pads, roads, etc. if needed), and the MRDS equipment is emplaced in a location where it can be made operable or the actual place where it is to be used and checked for completeness and functionality to the extent possible. Drilling personnel work with support equipment suppliers onsite to customize the pad appropriately and set up interfaces with power, water, compressors, and other required infrastructure.

5. Configure System: The MRDS BHA is configured with the high-pressure drill rig owned by the drilling contractor.

6. Drill Probe Hole: Drilling proceeds under the direction of the command center as it must be coordinated with the many other activities supporting rescue. The command center selects the drill site, and the mining company provides the driller with expected

subsurface geology/hydrology and mine conditions. The MRDS must be applied in a manner compatible with conditions that include explosive gases and must be compatible with supplying compressed air through a drill stem. The system must also be able to function with water entering the hole as well as in severe winter temperatures and conditions. The MRDS must include redundancy in its key elements, including replacement bits in case equipment is lost in the hole or damaged, and replacement of key functional elements if the MRDS is a complete drill rig.

7. Probe Mine Conditions: Once the hole enters the underground mine opening, it becomes a conduit for receiving information on underground conditions, including the condition of miners. It is used to probe mine conditions and aid in rescue operations. If miners are present, the borehole becomes a lifeline for sustenance and communication and in instances like Quecreek, it can be used to alter underground conditions to support the miners.

8. Drill Rescue Shaft: If the MSHA mine rescue capsule is to be employed, the drilling company must drill a large hole. The MRDS may in the future be developed to include the capability to drill large holes (24–30 inches), but at present it will be developed to drill probe holes (~6–8 inches) only.

9. Support Rescue Operations: The MRDS web site will be available as necessary to aid in the overall rescue effort.

10. Logging, Reporting, etc.: Drilling company personnel will document all steps of the application of the technology at the site, including anything that can contribute to process or technology improvement. Logs kept will note the following: activities from callout to return to standby; terrain; weather; timing of activities; required stopping or slowing points; successes and problems; equipment condition, maintenance, calibration logs; materials and infrastructure used; and any other relevant data that contributes to assessment of the application of the MRDS and future improvements. The log will include recommendations for required maintenance/replacement of parts that failed or for other reasons became compromised during use.

11. Inspections and Rig-Down: The equipment will be prepared for pick up by the transporting entity when it is time to return the equipment to its standby location. This includes breakdown to shippable form, securing in containers as appropriate, and removal of fuel and hazardous material as required. Broken MRDS equipment will also be retained and returned to the standby location for postmortem assessment.

12. Transportation: Equipment will be returned to the standby storage location.

13. Equipment Standby / Pre-Event Condition: When the MRDS equipment is received at its standby location, it will be examined for completeness, damage, and routine maintenance requirements. The equipment will then be serviced and made ready for potential redeployment as soon as possible

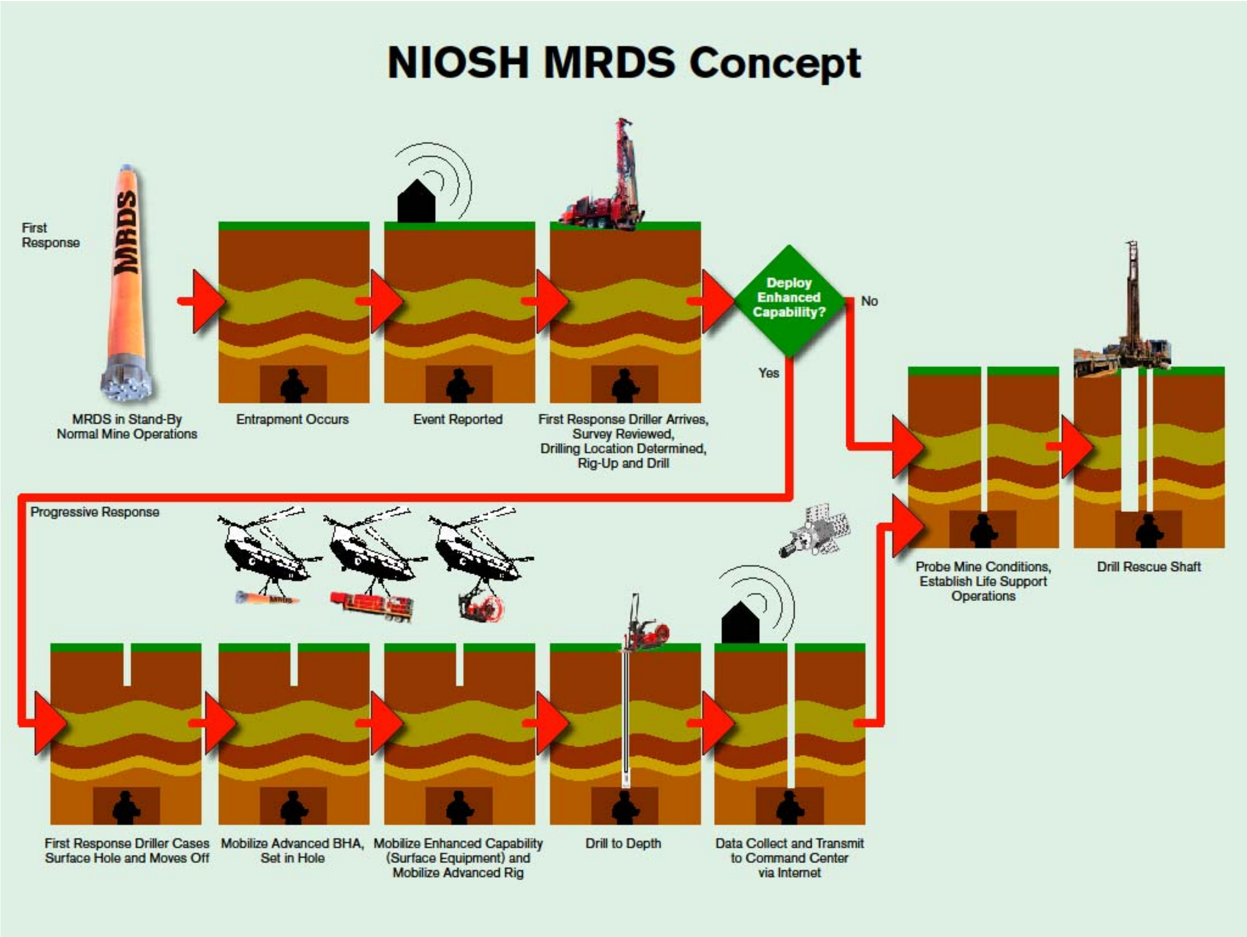


Figure 21. Concept of operations (CONOPS) for the MRDS (Photos courtesy of Numa, Schramm & Amkin Technologies).

A summary of potential interfaces with other equipment and activities is provided in Figure 22.

System				Activity																			
Major System Elements		Sub-System	Component	Pre-Event								Event								Post-Event			
				Standby								Event Occurrence, Recognition & Reporting	Deployment	Rig-Up & Checkout: Configure System			Drill	Probe Mine Conditions	Support Rescue Operations	Loging, Reporting, etc	Inspection, Rig-Down & Repairs	Transportation (Return Shipment)	Return to Storage & Standby
				Updates	Maintenance	Inspections	Qualifications	Calibrations	Replacement	Inventory	Test			plumbing connctions	electrical connections	data connections							
Mine Rescue Drilling System (MRDS)	Website	Database	Mine Information (Depth, Geology, Conditions)	x								x											
		Site Specific Information	Identify Site, Mine Conditions, Threats,…									x											
		Logistics	Maps, Driving Instructions, Flight Schedules									x	x										
		Event Mangement	Central Hub									x	x					x	x				
	High Speed Drilling System (Probe Hole)	Surface Equipment	Compressor		x	x	x		x	x	x		x	x	x		x				x	x	x
			Booster		x	x	x		x	x	x		x	x			x				x	x	x
			Turbo-Compressor		x	x	x		x	x	x		x	x			x				x	x	x
			Power Pack		x	x	x		x	x	x		x	x	x		x				x	x	x
		Downhole Equipment	bit						x	x			x	x			x				x	x	x
			hammer		x	x			x	x			x	x			x				x	x	x
			drillstring						x	x			x	x			x				x	x	x
			casing advancement systems						x	x			x	x			x				x	x	x
			casing						x	x			x				x				x	x	x
		Diagnostic Equipment	Sensor Sub		x	x	x	x	x	x	x		x		x	x	x				x	x	x
			DAQ system		x	x	x	x	x	x	x		x		x	x	x				x	x	x
			Drilling Advisory System		x	x		x	x	x	x		x		x	x	x				x	x	x
			Satellite Uplink		x	x	x	x	x	x	x		x		x	x	x				x	x	x
	Contractor Supplied Rig & Local Expertise	Rig	Standard Carrier	x	x	x	x	x	x	x	x		x	x	x	x	x				x	x	x
			Derrick														x				x	x	x
			Drawworks																		x	x	x
			Rotary Head																		x	x	x
			Power pack																		x	x	x
		Crew											x				x				x	x	x
Other Mine Resuce Systems	Communications	MSHA TV Probe																x			x	x	x
Post Mortem Equipment	Inspection, Survey, etc																			x			

Figure 22. Typical operations of the MRDS CONOPS.

8 Recommendations

The present study includes preliminary surveys of key areas in the wide range of information to be studied prior to recommendation of a final form of the MRDS. The following list of summary recommendations is drawn from detailed discussions contained within this report.

8.1 Summary Recommendations

- Locating miners underground occurs through various means, but probe boreholes remain a key method and can lessen the use of underground rescue teams.

- A specialized BHA is the proposed first-step MRDS engineered element because it is compact (quick deployment), works with moderately modified standard equipment and is not expensive to maintain.

- To be of value, MRDS technology must significantly improve drilling rates in sedimentary geologic sections that may be saturated.

- MRDS development can proceed in phases beyond the proposed BHA as a result of continued study to encompass improved practices with existing equipment and systems and discussions of potential improvements in made-for-purpose equipment.

- The specialized MRDS BHAs should be stored in strategic locations for quick transport to event sites.

- Any MRDS operation will have to mitigate potential explosive conditions related to drilling in a disrupted mine environment.

- The evolving MRDS will always operate within the MSHA emergency framework.

- MSHA emergency framework could be augmented with web features that better enable MRDS deployment and use.

8.2 Future MRDS Equipment and Methodology Development

Sandia is currently performing technical development of high-speed DTHH (down-the-hole hammer) drilling equipment and methodology with other federal funds that can be a leveraged contribution worth millions of dollars if future development of an MRDS system continues. The initial recommendations in this report are based on our preliminary data surveys and the early technical developments we are seeing in our ongoing drilling studies. We include in this report a road map for future technical development and a discussion of MRDS subelements and the types of testing we would pursue in future development efforts.

8.3 System Development Path

The following are recommendations from the concept design study:

- Develop an advanced BHA for mine rescue drilling technology based upon high-performance percussive hammer technology.

- Possible development of small, air-transportable compression equipment to support the power requirements of the MRDS; Current compression equipment is bulky and difficult to transport. It is used however for remote drilling operations and can likewise be transported for a mine rescue drilling situation. Small, air-transportable compression equipment could be developed to support the power requirements of the MRDS.

- Development of a compact nitrogen production unit for the MRDS should be considered to ensure explosive hazard mitigation when drilling into disrupted mine conditions with explosive potential.

- An alternative to nitrogen units would be development of an explosive atmosphere mitigation foam compatible with the hammer drill and suitable for breathable atmospheres.

9 Conclusions

The safety of people involved in underground coal mining is of great priority to all involved, from miners and operators to regulators and rescuers. A technology is needed that significantly reduces the time required to locate and potentially rescue miners trapped in underground accidents. Sandia has been tasked to perform this role with funding from NIOSH. Through this present study in reviewing current technical approaches, primarily based on technology developed under other programs, Sandia has analyzed mine rescue specific requirements to develop a conceptual mine rescue drilling approach. Sandia has demonstrated advanced hammer technology that is capable of drilling typical minelike geologies that may be encountered that can exceed commercial rates by more than a factor of 10. Sandia proposes development of a phased MRDS that accomplishes the following:

1. Development of rapid drilling MRDS equipment
2. Structuring improved web communication through the MSHA web site
3. Development of an improved protocol for employment of existing drilling technology in emergencies
4. Deployment of advanced technologies to complement mine rescue drilling operations during emergency events
5. Preliminary discussion of potential future “modified-for-purpose” technology for MRDS.

This phased approach allows for rapid fielding of a basic system for improved rescue drilling, with the ability to improve the system over time at a reasonable cost.

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Appendix A. List of Acronyms

ABH	adjustable bend housing
ANOVA	analysis of variance
BHA	bottom hole assembly
CBRN	chemical, biological, radiological, or nuclear (incident)
CO	carbon monoxide
CONOPS	concept of operations
COTS	commercial-off-the-shelf
CTU	coiled tubing unit
Dept.	Department
DOT	Department of Transportation
DTH	down-the-hole
DTHH	down-the-hole hammer
ES&H	environment, safety, and health
FAB	fresh air base
FEMA	Federal Emergency Management Agency
ft-lbf	foot-pounds force
FTP	File Transfer Protocol
GPS	Global Positioning System
HPU	hydraulic power unit
IP	Internet Protocol
KOMSL	Kentucky Office of State Mine Safety and Licensing
ksi	kilo pound per square inch
lbf	pounds-force
LWD	logging while drilling
MEO	Mine Emergency Operations (of MSHA)
MEU	Mine Emergency Unit (of MSHA)
MINER	Mine Improvement and New Emergency Response Act
MRDS	mine rescue drilling system
MSHA	Mine Safety & Health Administration
MWD	measurement while drilling
NAE	National Academy of Engineering
NIOSH	National Institute for Occupational Safety and Health
NMA	National Mining Association
NPU	nitrogen production unit
PDC	Polycrystalline diamond compact
PDM	positive displacement motor
POMSO	Plans, Operations & Military Support Officer
ROP	rate of penetration

RSS	rotary steerable system
Sandia	Sandia National Laboratories
scm/min	standard cubic meter/minute
SCSR	Self-Contained Self-Rescuer
S-MINER	Supplemental Mine Improvement and New Emergency Response Act
TH	top hole (hammer)
TOB	torque on bit
UCS	unconfined compressive strength
WOB	weight on bit
WOS	weight on string

Appendix B. Phase I Work Statement

The work statement under which the work reported here was undertaken is provided in this appendix. It should be noted that in the course of the work, a significant effort was directed toward Task 2.2, the field demonstration. Unfortunately, due to legal difficulties, we were unable to field the demonstration during the Phase I work. As a result it was decided that a demonstration could be mounted at the point where the initial BHA was actually built.

Phase I: Conceptual System Design and Early Drilling Demonstration

Task 1: Engineering System Design Study

The purpose of this effort is to develop a system concept of an MRDS that meets technical and program needs and to outline a developmental road map that leads to a fully deployable system through a staged process. Specific elements of this study will include:

1.1 Establishing Requirements – Discussions will be held with NIOSH, MSHA, the drilling industry, underground mining industry, mine rescue specialists, and others as needed to establish system operational and design requirements that will allow the development process to move forward. Information will be gathered, with assistance of NIOSH, on desirable equipment and drilling specifications, performance metrics, typical mine depths, lithologies, rock conditions, and other issues for use in trade-off studies. This information set will be used to establish a requirements basis for the drilling system and will feed the subsequent study sub-tasks below.

1.2 Develop a Concept of Operations – A CONOPS is a high-level vision of the how the system will be maintained, tested, deployed, employed in a rescue operation, retrieved, and stored through its lifecycle. Numerous possible application scenarios will be considered to ensure that the system concept developed will meet desired goals. This effort will also include a review of previous mine rescue efforts where possible to identify operational/technological issues and lessons learned.

1.3 Component Options/Trade Studies – Major system decision options will be examined and trade studies performed to narrow the potential design space and optimize the system concept to meet the functional requirements. A thorough review of current technology and practice will be performed with focus on technology gaps as well as necessary logistical and performance improvements for the mine rescue application. Trade studies considering options like power systems (type, location, fuel, down hole or surface), drilling method (hammer, rotary, or combined capability), hole stability methods (pipe, casing, sizes), platform size and configuration, etc. will subsequently be completed. Studies will be performed with consultation from drilling industry engineers to assure system concepts can be manufactured and will meet industry safety requirements. The result of these studies will provide input for specifying a preferred conceptual configuration.

1.4 Conceptual System Design and Specification – Using the results of the component options and trade studies, a concept for a preferred system configuration will be conceived that meets the foregoing requirements and is compatible with the envisioned CONOPS necessary for the MRDS. For the purposes of the engineering design study, this design will be mostly conceptual but will form the foundation for detailed engineering design developments in future phases.

1.5 System Development Path – Develop a road map for system development. Outline the developmental stages that could be successively built upon to achieve a full prototype system. The path to full system concept will consider constraints of budgets and time for design and successive builds. Successive generations will build on equipment and expertise gained in previous generations and will focus on incrementally improving mine rescue capabilities with the ultimate goal of a "fit-for-purpose" mine rescue system. The road map will outline anticipated technological developments that need to be pursued at each stage to make the next leap forward.

1.6 Reporting – This subtask provides for the documenting and production of Task 1 results in the form of a Sandia report that provides the details of the methodology and results of the system design study and provides the basis, along with the results of Task 2 for a decision to proceed with the development of the first-generation prototype MRDS.

Task 2: Initial System Development and Demonstration

The purpose of this task is provide initial data on drill and bit performance for the design of the MRDS and to demonstrate that the Sandia rapid-penetration drilling technology is feasible for application to mine rescue scenarios. The field demonstration will also provide valuable data on conditions at depth that are likely to be encountered and help support the development of a system concept that can accommodate a variety of field conditions.

2.1 Feasibility of MRDS Rapid-Penetration Drilling – This effort will focus on feasibility and applicability of Sandia rapid-penetration drilling technology to rock lithologies that are typical of what may be encountered in drilling into a coal mine. The testing will be conducted using the current Sandia rapid-drilling test bed. With assistance from NIOSH, Sandia will identify up to five rock blocks (approximately one meter cubed), support the excavation from the mine site, and arrange for shipping to the Sandia Albuquerque site. Selection of rock types and excavation locations will be mutually agreed upon with NIOSH to provide a reasonable test of the MRDS concept feasibility on the laboratory scale. Sandia will conduct a series of drilling penetration tests on the selected blocks. Numerous runs systematically varying drilling parameters and bit types will be performed. Data from each test will be recorded and analyzed to estimate the range of drilling parameters that should be explored in the field demonstration and to provide input to the system design studies. Based on the results, a decision as to whether to proceed with the field demonstration will be made.

2.2 Early Drilling Demonstration - The principal purpose of the early drilling demonstration is to feed the design study with some field-proven innovations as a starting point. Primarily, we will look at comparisons of rock reduction methods (e.g., hammer versus rotary bits) for typical Eastern coal mine lithologies and depths. A demonstration site will be chosen based on evaluation of available sites identified by NIOSH. Sandia-designed hammers and other previously developed equipment will be compared with commercially available alternatives for speed and the ability to penetrate a variety of lithological layers without adversely affecting the drilling process. Drilling and support equipment will be provided and operated by local contractors. Sandia will oversee operations and provide all data collection, analysis, and reporting.

2.3 Reporting – This subtask provides for the documentation and production of the results of Task 2 in the form of a SAND Report detailing the methodology and results from the laboratory and field tests of the MRDS drilling technology.

Appendix C. Recent Mine Accident Summaries

Quecreek #1 Mine, Black Wolf Coal Company, Inc., Quecreek, Somerset County, PA, July 2002

July 24, 2002 at approximately 8:45 P.M. miners working Quecreek Mining Company, Inc.'s Quecreek #1 Mine breached a barrier and broke into the abandoned Saxman Coal and Coke Company's Harrison #2 Mine resulting in millions of gallons from water from the Harrison #2 flowing into Quecreek #1 (U.S. Dept. of Labor 2003). The water came in with great quantity and force. Nine men were trapped 76–78 hours and eventually rescued through a large borehole using an MSHA rescue capsule. The cause of the accident was an undated, uncertified map on file for the Harrison #2. This flooded, abandoned mine up dip from Quecreek #1 was thought to be several hundred feet away. Wet conditions at Quecreek #1 resulted from overlying aquifers and a nearby fault and possibly masked early warning of water influx as mining neared the Harrison #2. The Upper Kittanning coal seam was being mined by remotely controlled continuous mining machines.

Miners knew water was flooding in ~8:45 P.M. when the operator of a continuous mining machine looked toward the face and could not see the machine or its lights. The surface was notified of "major water" entering the mine soon after the breakthrough. At 9:00 P.M. the mine superintendent was called. At ~9:30 P.M. a district mine inspector was notified, and ~9:42 P.M. an MSHA field office manager was notified. By 9:50 P.M. a drilling company was called, and a rig to drill the 6.5-inch hole arrived onsite at 12:00 A.M. Two companies that had surveyed at Quecreek were called at 11:05 P.M. Two surveys for a proposed hole were done—one GPS, one traditional. Onsite were multiple MSHA groups, the Pennsylvania Bureau of Deep Mine Safety, other rescue groups and a U.S. assistant secretary of labor for Mine Safety and Health.

Water under great pressure created swift flow that inhibited swimming or walking and quickly disabled equipment and entered escape routes. The miners tried to leave but decided they were cut off and went back to an area near the face and built a barricade. As they built, at 5:06 A.M. on July 25, the 6.5-inch hole penetrated the mine after 2 hours 16 minutes outby the location of one of the barricade walls under construction. This wall and others were reworked, but the last wall was not finished in time to beat the rising water and had to be abandoned. When the drill penetrated, they tapped on the drill steel to let the surface know they were alive, and the drill string was lifted and rotated in response.

Through the drill string, air from the drill rig compressor was pumped in, expelling air at the surface with oxygen levels at ~17% then 19.3%. A seal was made around the top of the hole using inflatable bags from the fire department, and the compressor continued running. The air was much improved for breathing when the borehole penetrated the air pocket where miners were, though one miner said that oil vapors from the compressor system caused him some ill effects. Water rising caused the miners to retreat from the drill-string area. The miners estimated they had about an hour left based on how fast the water was rising, and some tied themselves together and some wrote notes to family. They moved again and made a barricade, but over time the water rise stabilized and eventually began to recede. On July 27 the miners went back to the 6.5-inch hole about an hour before the rescue hole broke through about 20 feet outby the 6.5-inch hole. The miners arrived on the surface between 12:55 and 2:45 A.M. on July 28.

A second drilling company started the 30-inch hole at 6:45 P.M. on July 25, for the 21.5-inch rescue capsule that had arrived at 9:40 A.M. The hole was at 105 feet by 1:12 A.M. on July 26 when the bit was lost in the hole and a fishing tool was brought in. A new 30-inch bit was acquired and drilling started from the surface again, outer cutting bits got damaged and the hole was finished with a 26-inch bit. A second rescue hole had started at 10:25 A.M., reached 28 feet by 11:30 A.M., and 204 feet by 1:15 P.M. on July 27 when the bit broke, was lost in the hole, and operations stopped. Rescue hole one reached a controlled "stop depth" by 1:38 P.M. and had to wait while the water level went down. A seal plate was placed on top of the hole during final drilling to avoid losing pressure in the miners' air pocket. Cut through was at 10:13 P.M. at 239.6 feet. Using an airlock chamber at the top of the hole was considered, but its use at a mine was unproven, so it was not tried.

A 6-inch hole in a corn field was drilled in the Mains starting at 6:30 A.M., with total depth at 290 feet at 11:00 A.M., and was later drilled out to 15 inches and a pump was installed downhole. Another 15-inch hole bottomed in a coal pillar and a 17.5- inch hole was drilled for a pump. Two other holes were drilled into the mine elsewhere. Blasting into the mine was also tried unsuccessfully. Two small holes were drilled into Harrison #2 to look for escaped miners. On July 27 three new dewatering holes were started in the cornfield as 12.25-inch holes, to be enlarged to 24 inches.

Sago Mine, Wolf Run Mining Company, Tallmansville, Upshure County, W. VA, January 2006

On January 2, 2006, at approximately 6:26 A.M., an explosion occurred at Sago Mine, Wolf Run Mining Company, Tallmansville, Upshure County, West Virginia (U.S. Dept. of Labor 2007a). There were 29 miners underground, and carbon monoxide poisoning took 12 lives and seriously injured one miner. The explosion occurred in a sealed off, formerly mined area, most probably caused by a lightning strike igniting trapped methane. The explosion released carbon monoxide from the sealed area into the working area, blew out seals, destroyed and tossed around equipment, and created smoke and soot. The wreckage blocking their primary escape exit caused the trapped miners to turn around, band together, barricade themselves, and wait for help. The first indication of a problem at the surface was a carbon monoxide sensor alarming at 6:26 A.M. Early reports to the surface left uncertainty as to cause because they were piecing together observations from different viewpoints underground that had differing conditions of airflow, dust, smoke, and debris. It was determined that at approximately the same time as the explosion, someone on the surface observed a flash of lightning. Two continuous mining machines, in two overlapping 10-hour shifts had been mining the Middle Kittanning coal seam (average mining height 7') through five drift openings. Bottom mining of the lower bench of the seam was conducted in some areas, creating high, unsupported coal ribs. The mine was wet but was not considered very gassy. Ventilation removed methane, which in October 2005 was 90,500 cf/day.

Mine management was called about the accident by 7:00 A.M., mine rescue soon after, and MSHA was finally reached at 8:28 A.M. after several earlier calls went to voicemail probably because some were on holiday. By 8:32 A.M. MSHA issued a 103 (k) via telephone, and at 8:30 A.M. a representative of West Virginia Miner's Health & Safety Training issued an order to preserve the scene, both of which restricted activities at the site. MSHA headquarters was contacted about 10:00 A.M., and their Mine Emergency Unit (MEU) was mobilized. There were multiple rescue groups onsite and an MSHA robot that became disabled underground. The mine operators submitted requests to send rescuers into the mine at 4:00 P.M., and the first rescuers were reluctantly allowed underground about 4:55 P.M. because carbon monoxide levels were still high, methane was present, and the atmosphere had not stabilized. Carbon monoxide was present at the drift openings pit (>2000 ppm, up to 4400 ppm), and they worried it might be around some buildings.

The mine's chief engineer was responsible for developing coordinates for and planning boreholes. He was notified at 10:30 A.M. of the accident and called the company that had been mapping the mine. His own GPS was hindered by a lack of signal, but he received a map from the mapping company by an FTP site and used a planimetric map of the surface as a supplement. He suggested a site at ~1:35 P.M. in an area with gentle grade and asked for a location confirmation from a mapping grade GPS that had arrived ~2:07, but it too had poor signal strength. Signal strength, number of satellites contacted, weather, structures, and trees affect GPS location quality. About 3:30 P.M., after permission was obtained from a landowner, construction was begun on a road to access the surveyed point over the 2nd Left Parallel work area of the lost miners. A site was prepared for a borehole within three hours. The command center gave permission to drill the hole, but a survey crew arrived at 6 P.M. and started a survey, working from permanent monuments at the mine so the drilling was delayed. The survey grade GPS they had could not get adequate radio communication to work. Eventually, a surveyed location was accepted and drilling started at 2:45 A.M. The borehole penetrated the mine at 5:35 A.M. at 258 feet depth, sampled the air, and tapped on the drill string to elicit a response from the miners. No response came. They lowered a camera but did not find the miners. A second borehole was drilled in the area starting at ~ 6:50 A.M. that reached 360 feet (~30 feet above the mine) at 2:24 P.M. and was not finished because teams were underground. It was subsequently finished to aid mine recovery. A third borehole was started at ~2:35 P.M. but stopped short because of 60–80 gpm water inflow.

The underground rescue teams found the first miner, who had died separated from the others, at 5:20 P.M. The rescue team advanced more quickly than was allowed by air-locking protocol and risked being out of communication by overreaching the hand-held's capabilities. Communications cut in and out and had to be relayed by running back and forth, and as a result, misinformation was communicated to the surface about the condition of the men when they found them. The team that found the barricaded men entered at 11:17 P.M., had the one living miner at the surface at 1:00 A.M., and exited at 1:20 A.M. The rescue description does not have a detailed time line for the rescue in this time interval.

Kentucky Darby, LLC, Darby Mine No. 1, Holmes Mill, Harlan County, KY, May 2006

On Saturday, May 20, 2006, at ~1:00 A.M., an explosion occurred in a sealed, formerly worked area of the Kentucky Darby, LLC, Darby Mine No. 1, 26 miles east of Harlan, Harlan County, Kentucky (U.S. Dept. of Labor 2007b). Five miners lost their lives, and one was hurt. A metal roof strap, placed for roof support, and passed through an isolating seal was cut with a torch igniting methane behind the seal, killing two men from the explosion and damaging structures, including ventilation. Three miners in a nearby section died from carbon monoxide poisoning with smoke and soot inhalation. The cause was failure to follow basic mine safety practices and inadequate miner training in use of self-contained self-rescuer (SCSR) equipment that should sustain men for one hour in an accident. The company was cited for six conditions/practices that contributed to the accident.

Mining was in the Darby coal seam, with an average thickness of 56 inches, and in some areas, the overlying Owl coal seam, with an average thickness of 36 inches, resulting in mining heights from 40–144 inches. The daily methane liberation rate was 38,707 cf/d at last inspection. There was one advancing room and pillar section, mined by a continuous mining machine, using a battery-powered scoop and a roof-bolting machine, with coal transported to the surface by four conveyor belts. There were two production shifts and one maintenance shift daily, six days a week.

Postaccident evidence suggests two men were using a torch to cut metal roof straps for roof support, which had been left in place passing through and behind a seal that isolated the formerly mined area. The strapping made it impossible to emplace the wood planking between the seal and the roof, a requirement of the ventilation plan. They had but were not using a methane detector that would have alarmed, indicating not to use a torch. They were killed and blown 240 feet and 340 feet from the seal area. The crew exiting the mine ~1:00 A.M. felt the explosion and saw debris coming out of the mine portals and thought a roof or high-wall collapse had occurred until the odor of burned coal reached them. Another underground crew heard the explosion and tried to leave, encountering dense smoke and eventually debris that stopped their exit by vehicle. They did not have a carbon monoxide detector. This crew of four men parted ways. The one who immediately started outby following a high-voltage power cable was eventually found after being overcome by carbon monoxide and reviving to make some progress to where he was found. The other three tried to escape by going inby toward a power center. They donned their SCSRs and started outby but succumbed to carbon monoxide at different locations along a similar escape path, with the longest surviving person getting ~1600 feet while on SCSR, over 2000 feet short of a portal.

The MSHA district office was notified at ~1:05 A.M., and they notified other MSHA entities, including the MEU. A 103 (k) order was issued at 1:54 A.M. by MSHA. At a mine fan, they measured 2.6% methane and over 500 ppm carbon monoxide, indicating a fire or explosion. A Kentucky Office of State Mine Safety and Licensing (KOMSL) representative arrived, later followed by rescue teams from this group. At 3:10 A.M. a rescue team found the surviving miner, and one transported him out while another continued to find the others that the survivor had said were several crosscuts behind him. The rescuers were stopped by carbon monoxide readings from 80 ppm to off-scale and had to establish a fresh air base. Against protocol, rescuers advanced from this base leaving it unmanned with backup. The KOMSL group eventually found one of the dead at ~4:30 A.M. by seeing his cap lamp and found high carbon monoxide concentrations. He was left in place. At ~5:16 A.M. two more dead were found by another rescue group. About 8:45 A.M. the last two victims were found by a rescue team. After ventilation was adequate to remove high concentrations of carbon monoxide in the area where victims were found, their bodies were removed about 10:55 A.M. They continued to monitor air and check ventilation for several days. The accident investigation began on May 23, 2006.

Escape training impacts where the men might be found after an accident. The men had tried to follow training and leave by the primary escape way, until debris stopped their personnel carrier. Then they did not try the alternate escape way, but went another way. The man who was found also was not following the primary or alternate escape way, but eventually went to an intake entry where he was found. It was later found that the escape drills were not properly done, the men had not practiced traveling out of the alternate escape ways, and some of the men had not had training. In addition, there were not accurate maps showing active workings and escape routes posted (as required) above and below ground

Crandall Canyon Mine, Genwal Resources, Inc. Huntington, Emery County, Utah, August 2007

On August 6, 2007, at 2:48 A.M. at Crandall Canyon Mine, Huntington, Utah, a coal burst occurred during pillar recovery in the Hiawatha bituminous coal seam while the section crew was in the area (US Dept. of Labor 2007c). The barrier pillar near crosscut 139 was being mined and failed and failure propagated outward collapsing overstressed pillars for about half a mile. Coal was expelled into the mine openings where the burst occurred, likely causing fatal injuries to six miners. As barrier pillars failed north and south of the accident point, breaching sealed off areas. The section was inundated with lethally oxygen-deficient air which may have contributed to the miner's deaths. The 3.9 seismic event initiated by the accident was felt at the mine office three miles away. The Mine Supervisor started notifying others about 3:30 A.M., including MSHA at 3:43 A.M. MSHA issued a 103 (k) order at 4:41 A.M. and various state, federal, and other rescue and emergency people arrived onsite about 4:30 A.M., including the federal assistant secretary of Labor and Bureau of Land Management. Those underground at the time of the accident started investigating and provided some information as to where the men were. Men from the rescue groups started in about 4:00 A.M., with repair and rescue under MSHA planning starting about 6:00 A.M. They tried getting to the accident zone through various entries and encountered debris, sometimes up to the roof, and depleted oxygen levels. Other teams began work on repairs, including ventilation controls. About 11:00 A.M. they tried sending air to the miners through a water line, but no communication was established, though one trapped miner had a PED device. They breached a seal into the sealed area north of the accident zone and found oxygen at 6–6.8% and 62 ppm carbon monoxide and impassable roof falls in three entries. They experienced the ground "working" and bursts in the fourth entry and retreated. At 5:02 A.M. they tried a fifth entry behind the seal, but a 2.6 seismic event burst occurred just at that time and they had to retreat, resealing the area with a curtain. This event compromised their fresh air base, flooding it with low oxygen air.

On the afternoon of August 6, the mining company started removing material from one of the impassable mine entries (No. 4), but on August 7 at 1:13 A.M. a 2.8 seismic event burst occurred in the clean-up area. No one was injured, but ~300 feet of cleared entry was partially refilled and ventilation controls were impacted. They decided to try the No. 1 entry and MSHA deployed a small portable seismic detection system transported from Pittsburgh, PA. Deployed underground in two entries, it could locate people over short distances, up to ~200 feet, but its sensors detected no responses from the miners through either roof bolts or water pipe. It was not used again. On August 8 the 103 (k) plan was modified. Entering the No. 1 Entry of South Barrier began under that plan. They used wooden posts backed by chain link fence to guard against pillar bursts and installed roof-to-floor supports, and clean-up started ~6:00 P.M. on August 8. They reached inby crosscut 122 and by modification to the plan August 10, two people were allowed to go in front of the continuous mining machine. Attempts by these two in Entry No. 1 and No. 4 were not successful. As clean-up advanced to inby crosscut 123, they saw that the south barrier rib had advanced up to 10 feet during the accident, tearing up the roof support. August 11 plan modifications required more precautions in advancing the clean-up as they observed that ground stress had affected pillars in the Main West entries and North and South Barrier workings. The August 13 plan was even more prescriptive, and the clean-up had reached crosscut 125 by Entry No. 1. They were inby crosscut 125 on August 15 at 2:26 A.M. when there was a coal burst and a 1.2 seismic event that damaged the mining machine and ventilation controls, but they were back at work by 4:00 A.M. However, there was "rock noise" outby cross cut 119 in Entry No. 1, and they set up convergence stations for monitoring.

In the morning of August 16, the miners went in Entry No. 1 about 6:25 A.M., and MSHA checked the convergence stations and ground conditions and found no changes. At 10:04 A.M. a coal burst occurred in the pillar between Entry No. 1 and Entry No. 2 with a 1.5 seismic event that displaced ~ 4 feet of pillar rib and filled the entry on one side of the mining machine to about 2.5 feet, but they cleaned up and continued. At 1:30 P.M. MSHA again checked convergence and made observations in Entries 1, 2 and 4, seeing no significant changes. By the end of the day shift, the cleanup was close to crosscut 127. At 6:38 P.M. as the crew worked on ground support, the coal pillar between Entry No. 1 and Entry No. 2 burst. Coal flew violently across the entry in a 1.9 seismic event and threw RocProps, steel cables, chain-link fence, and a steel channel that struck the crew. Heavy dust and oxygen-deficient air from inby flowed over the crew and could not be cleared quickly because of damaged ventilation controls. A survivor called on the phone for help, and others feeling the burst came to help. Though help came quickly, three men died and six were seriously injured. A panel of ground-control experts began evaluation of the risk to determine whether they could suggest effective ground-control methods in order to continue. They concluded that rescue was too risky and that there was no way to predict and safely control the subsurface conditions.

Seven boreholes were drilled from the surface to the mine workings. Three were during underground rescue work and four after the August 16 accident. The drill sites were in rugged mountain terrain. The first rig onsite was helicoptered in and could only drill a 3-inch hole using a polycrystalline diamond compact (PDC) bit, so no equipment could be lowered. The second rig was driven in, drilled six holes that started at 14.75-inch diameter, finishing from 20 feet to total depth with 8.75-inch diameter using hammer drilling. The seven holes were from 1,414 feet to 2,039 feet deep and took from 36 hours to 59.6 hours to drill. The six larger holes were drilled with direction control and reached their target areas. The last four holes were drilled to continue looking for the victims of the August 6 accident after the second accident when underground rescue was determined to be too dangerous. Information from the boreholes contributed significantly to obtaining data on underground conditions in the area where the men were lost. In the end, the men were left entombed and the mine was closed.

Appendix D. Geology Survey

The depositional environment in which coal is formed in minable amounts has some commonality in mining provinces as geographically separated as Pennsylvania and Utah, areas represented in two of the mining accidents discussed in this report. A brief description of the general geology of coal-producing sections in the area of Quecreek (Pennsylvania) and Crandall Canyon (Utah) will serve to show the similarities and the general nature of geologic sections an MRDS must penetrate. Though hydrology is important, it cannot be generalized as readily as can geology because hydrology varies with very localized conditions, whereas the depositional sequences that produced the geology were widespread geographically and persistent through time.

In the Appalachian Basin of Pennsylvania and in the Illinois Basin, coal was often deposited in geologic sections that were cyclical, sometimes called cyclothems (Krumbein and Sloss 1963, 536–538). These deposits occurred in the Pennsylvanian Period on an unstable shelf or interior basin. Sedimentary deposits that produced coal in these conditions were generally marginal marine, lagoon, swamp or other low, wet, plant-rich areas where the sediment supply and water depth shifted through time. A given point on the landmass could receive sand or silt as sediment source areas rose up, were eroded, and shed sediment that was carried by streams onto a low plain bordering a large inland lake or shallow marine area. As sources are eroded down, sand is succeeded by mud, and eventually the plain is occupied by marshes and swamps that produce the organic material that becomes coal. As sea level rises on the unstable shelf, the swamps can be inundated first by marine muds, then by marine limestones as water deepens. Eventually the sea becomes more restricted, and as source areas again start shedding sediment, mud accumulates and the area shallows and becomes brackish, leading to emergence of the area as the sea recedes. At any given point the land emerges, is inundated, and reemerges as the lake or sea, and the sediment sources interact with the unstable shelf tectonics. This creates a stacked section that in a cyclothem is from bottom to top (oldest to youngest): (1) fine-grained, sandstone and siltstone, massive- to thin-bedded with plant remains; (2) gray sandy shale; (3) fresh water limestone nodules or discontinuous beds, usually nonfossiliferous; (4) underclay, lower part calcareous; (5) coal; (6) gray shale, iron present, rare marine fossils; (7) limestone with marine fossils; (8) black, laminated shale, marine fossils; (9) limestone with marine fossils; (10) gray shale, sandy at the top; marine fossils in lower part. Not all of these members are always present, and the thickness of individual members may vary. The Allegheny Formation of which the Upper and Lower Kittanning Coal is a part was formed in this manner.

In the coal-producing Blackhawk Formation in Utah, the marginal marine-type environment developed coal-forming plants in lagoons paralleling a shifting coast line crossed by deltaic deposits and distributary channels (Dubiel et al. 2009). Lagoons with rich vegetation and muddy sediments formed behind barrier bars in a delta plain-back barrier situation. The sediments were sandstone with interbedded siltstone and shale, siltstone with interbedded sandstone and shale, and shale and lagoonal organics that became coal. This series of beds is stacked in the Crandall Canyon Mine area with the shalier, more lagoonal beds toward the lower, coal-rich part of the section and with sandstone becoming more dominant up-section. This section lacks the marine limestones of Appalachian and Illinois cyclothems but resembles them in the stacking of alternating sand-dominant, silt-dominant, shale-dominant, and coal beds that represent a shifting shoreline with rich vegetation growing in quiet, muddy areas that alternately become sediment-filled and more inland, and get transgressed by deepening water.

Appendix E. Survey and Applicability of Available Drilling Technologies for the MRDS

A survey was conducted to identify candidate drilling technologies that could be used to develop the MRDS. These technologies are summarized in this appendix. This discussion is not intended to be a primer for drilling but a snapshot of technologies that may be pertinent for mine rescue drilling based upon specific requirements. To facilitate clear presentation of the elements surveyed, each section contains a high-level statement about the technology and details. Information gathered during this survey led to our recommendation for future development of a high-performance BHA using hammer-drill technology and high-compression drilling. Other information is applicable to our recommendations for future assessment of potential future technology development and further development of improved protocols for employment of existing drilling technology to improve borehole emplacement rates.

E.1 Rock Reduction Technologies

Rock reduction refers to the down-hole process of breaking rock. Conventional techniques include percussive drilling, rotary drilling, and advanced techniques.

E.1.1 Percussive Drilling

Percussive drilling is accomplished by percussive loading a bit face to penetrate the rock. Down-the-hole hammers (DTHHs) and top hammer (TH) technology are both considered percussive techniques. These techniques primarily differ in the location of the impact source and the fluid used to generate impact power. DTHHs provide percussive energy directly at the bit and are typically powered by a gas that is delivered through the drill string. This gas also serves to circulate rock cuttings out of the hole. THs are located on the surface, use the drill string to transmit percussive energy and are hydraulically powered. Air is separately circulated through the drill pipe for cuttings removal. Although there are commercially available TH tools that meet some performance requirements for smaller-diameter blast hole applications, this method was discarded for the MRDS application because it is depth limited. There are 4-6% energy transmission losses between pipe joints, and it requires discontinuous operation that reduces the overall penetration rate when rock reduction is terminated during joint changes. This energy loss with depth and intermittent operation can be mitigated with DTHH technology because of its proximity to the bit.

A downhole pneumatic hammer is, in principle, a simple device consisting of a ported air feed conduit, which is more commonly known as a feed tube, a check valve assembly above the feed tube to prevent ingress of wellbore fluids into the drill, a reciprocating piston, and a drill bit and associated retaining hardware. A typical commercial layout is presented in Figure E-1. The typical valveless device, for example, possesses on the order of 15 components. The reciprocation of the piston is accomplished by sequentially feeding high-pressure air to either the power chamber of the case (the volume that when pressurized moves the piston towards the bit shank) or the return chamber of the case. The regulation of the air flow can be accomplished either by use of passages machined into the feed tube, piston body, and hammer case or a combination of active valving and porting through either the piston, case or an additional sleeve.

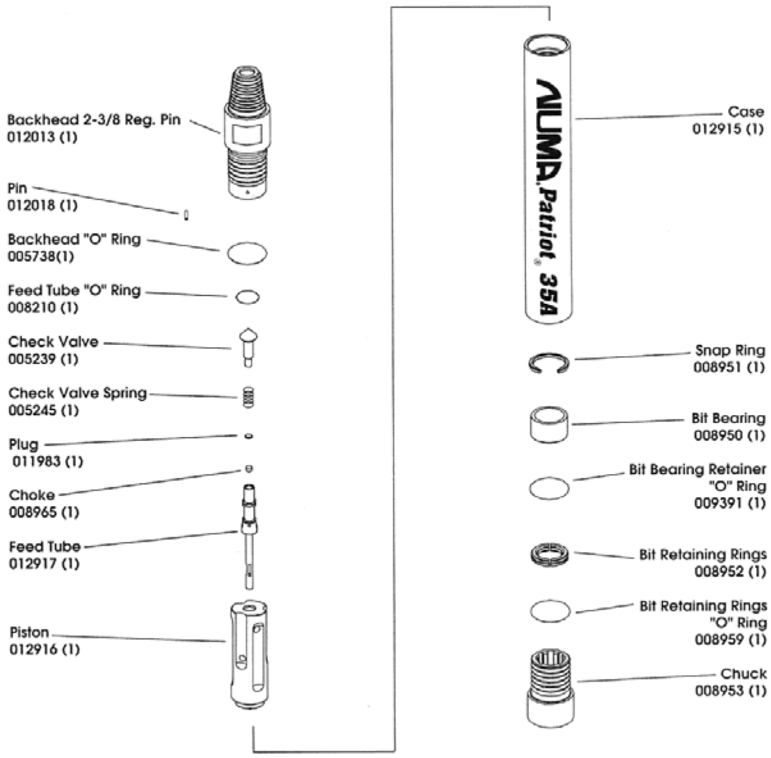


Figure E-1. Exploded view of typical commercial DTH hammer (Courtesy of Numa).

Hammer bits rely upon transmission of the kinetic energy from the hammer piston to the bit to penetrate the formation. This energy transmission process must be as efficient as possible to maximize the rock penetration and removal for each impact from the piston on the bit shank. An isometric view of a hammer bit is shown in Figure E-2. The distribution of the buttons across the face of the bit forms the cutting structure of the bit. Generally, the buttons have a sharp point that allows them to penetrate the formation with each successive blow from the hammer piston. The bit is incrementally rotated to effect removal of the rock cuttings generated by the penetration and to index the bit over fresh rock for the subsequent penetration. The bit face includes nozzles that direct the exhaust air stream from the hammer across the face of the bit to flush the cuttings away from the rock surface. The percussive drilling industry has adopted a standard of 350 psi as a nominal operating condition for DHHs.

Hammers are typically used in brittle rock where the impact energy from the piston against the bit shank can be effectively transmitted into the rock to produce an incremental penetration per blow. The benefit of hammers, however, is the incremental rotation of the bit face to strike a new rock area allows them to additionally function as a drag bit.

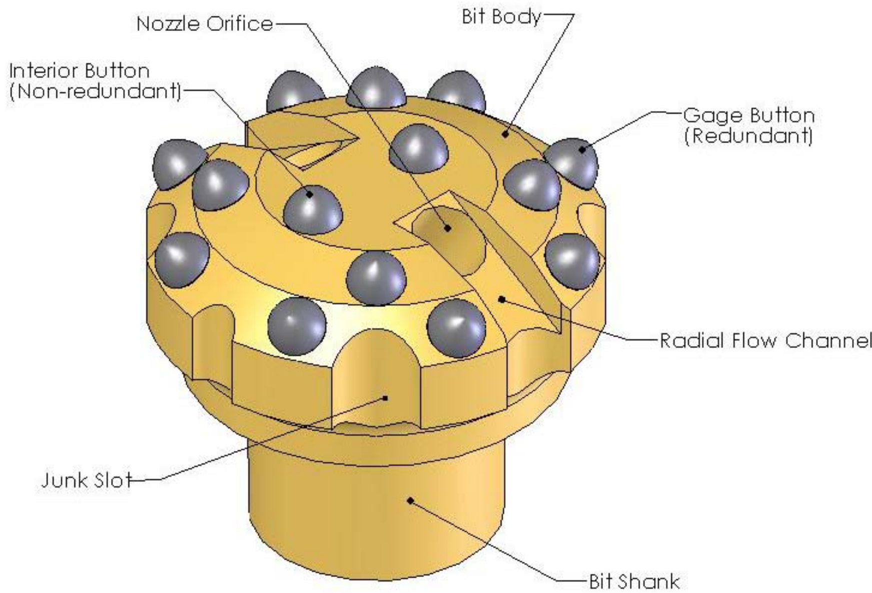


Figure E-2. Computer-generated solid model of a hammer bit.

E.1.2 Rotary Drilling

Rotary drilling employs various types of drill bits and variable methods of advancing these bits downhole. Circulated fluids are used to remove the rock chips from the hole, and the present study does not examine drilling fluids in detail. It was observed previously in the report that part of Sandia's proposed future work would be to investigate various drilling fluids that could suppress explosion potential in the postaccident mine environment.

Drag bits are commonly used to drill sedimentary formations. PDC (polycrystalline diamond compact) bits are a type of drag bit that has blades equipped with hard cutting elements made from polycrystalline diamond (Figure E-3). Since their inception in the early 1980s, PDC bits have been used to drill progressively harder rock and are now routinely used to drill rock with an unconfined compressive strength (UCS) in excess of 30 ksi. The bits are subject to overheating in the absence of effective cooling from a drilling fluid. Their high cost has historically limited their application to the oil and gas industry although they are recently being used for mining applications.

Figure E-3. PDC bit.

A roller-cone bit penetrates the rock by crushing the formation beneath the indenters on the cones that are rotated against the rock as the bit body is rotated. Roller-cone bits (two-cone or tri-cone) are predominantly used for drilling hard rock at greater depths. They either have teeth that are milled into the cone (mill tooth) or indenters (tungsten carbide or PDC) that are pressed into recesses in the cone surface. Roller cones are available in sealed configurations to extend the life of the bearings supporting the cones.

Impregnated diamond bits consist of natural diamond set within a tungsten carbide body. They penetrate the rock primarily by a grinding operation. They are able to penetrate very hard rock but are hampered by slow penetration rates.

Downhole motors are often used with rotary drilling to generate rotation downhole. This allows the bit to be rotated downhole to complement directional drilling technologies. Available options include positive displacement motors (PDMs) and mud turbines.

Various companies are developing downhole tractors that develop downhole drive motions to thrust a tool into an existing wellbore or develop traction for drilling. Downhole tractors are available in both hydraulic and electromechanical drives. They can be used in conventional systems with either jointed pipe or coiled tubing, although they are more prevalent in coiled tubing systems. The chief limitation of downhole tractors is they are long and may be cumbersome to work with given the complexity of the tool operation.

E.1.3 Advanced Rock Reduction Techniques

As part of our Phase I work, a variety of other techniques have been researched for penetrating rock. These include unconventional systems such as thermal/spallation, rock melting, water jets, chemical dissolution, and other methods subject to past and current research. However, none of these alternatives are adequate for this application. Although providing potentially promising high-penetration-rate drilling, these techniques are not practical for application to an MRDS.

E.2 Drill Rigs

Many conventional rotary drilling systems apply WOB, or thrust, by using drill collars—massive steel tubulars that rest on top of the bit and transmit thrust forces to the bit. The use of drill collars to transmit WOB to the drill bit means that only those tubular elements below the drill collar will be in compression. The balance of the drill string above the collar is in tension. The amount of WOB applied to the bit is regulated by pulling up on the drill collar. Many drill rigs use a block-and-tackle–based system to support the drill string in the hole. A brake on a drum hoist is used to control the amount of tension in the wire line supporting the travelling block that supports the drill string.

Conventional rotary drilling systems can generate rotation at the surface or downhole, depending upon the application. Historically, drill-string rotation has been introduced at the surface through a rotary table with a square opening for a kelly to pass through. The kelly is fastened onto the top of the drill string. During drilling, rotation of the rotary table rotates the kelly and hence the entire length of drill pipe.

More recently, top drives have become popular for introducing rotation at the surface. Top drives are hydraulically driven motors that ride up and down the mast on a structural steel rail fastened to the rig. The top drive includes a drill-string tool joint that is threaded directly to the drill string (usually through a saver sub). The top drive introduces rotation to the entire drill string while the drilling torque is reacted through the structural rail guiding the top drive.

Rotation can also be introduced downhole to the bit and other BHA components through the use of PDMs mounted in the drill string just above the bit. These motors operate off the hydraulic power in the mudflow pumped to the bit for bit coolant and cuttings removal.

E.2.1 Conventional Drill Rigs

For a shallow drilling system requiring the absence of drill collar, the WOB must be generated by developing a thrust force that is applied to the drill string. One way to generate the force at the surface is by a mechanism that forces the drill string into the well. Most conventional drilling rigs that are rapidly deployable truck-mounted units have capability for developing a thrust force in the drill string. These rigs are typically used for water-well drilling, drilling exploratory holes for mine exploration and coring operations. Some of the drill rigs common to the Appalachian region are Ingersoll Rand RD20, Atlas Copco T3/T4, Schramm rigs, and others.

Coiled Tubing Units (CTUs)

Recent developments in pursuit of shallow gas and geothermal heat pumps have allowed coiled tubing drilling technology to be made available in small, compact units. Figure E-4 is a CTU available from AmKin Technologies (Tomball, TX) for drilling small-diameter, geothermal heat pump wellbores. The benefit of CTU technology for an MRDS is the continuous conveyance of the drill pipe (tubing) into the hole during the drilling operation. Additionally, there is a continuous hydraulic connection to the downhole components, which may be important for certain BHA configurations. An additional advantage of this unit is its small size and transportability.

Figure E-4. CTU (coiled tubing unit) (Courtesy of AmKin Technologies)

E.3 Air Drilling Services

E.3.1 Compressors, Boosters

Most percussive drilling is accomplished using compression equipment that is transported to the drill site. For water-well drill rigs, a diesel-powered compressor is mounted on the truck frame. These units typically produce approximately 950 to 1,150 cfm at sea-level at 350 psi, which is adequate for most water-well/shallow drilling projects. Auxiliary compressors are transported in as needed to provide additional flow when drilling larger-diameter wellbores. Multiple compressors are required to provide suction flow for a reciprocating piston booster to increase the air pressure delivered to the rig standpipe. Boosters are capable of elevating the pressure to a level approaching 2,000 psi.

E.3.2 Nitrogen Drilling Services

Drilling with an oxygen-deficient gas could be used to help prevent explosive hazards. Coal dust cannot be ignited at oxygen levels below 11%, regardless of coal concentration (Cashdollar, 1996). Drilling with a nitrogen-rich gas, and thus oxygen-deficient, would mitigate the explosive threat from coal dust. Nitrogen production units (NPUs) are routinely used when drilling into hydrocarbon-bearing formations. These units use polymer fibers to separate the nitrogen from the ambient air stream. Purity levels of 95% are routinely achieved. Typically, twice the needed air volume is provided to the NPU to develop the required flow rates. NPUs are commercially available and strip nitrogen from the air. The nitrogen gas could then be compressed and used in place of the compressed air. The down side to these systems is their initial expense ($250k to $1,000k), size and weight (13,000 to 29,000 lbs). Also of concern would be whether the volume of air from a single stripper would satisfy the demand of the desired drilling rate.

Alternatively, nitrogen can be transported to the drilling site in tube cylinders to provide a gas source. Given the large expansion ratio of nitrogen from a liquid to a gas phase, liquid nitrogen could be a viable alternative to a nitrogen stripper. With an expansion ratio of ~694:1, a tank of liquid nitrogen could be driven or flown by helicopter to the MRDS location and provide the nitrogen gas needed for deep drilling. The advantages to using liquid nitrogen over a nitrogen separation system are (1) ease of availability, (2) low cost, and (3) minimal required system maintenance. A major disadvantage could be producing the flow rate required by the MRDS. As the liquid nitrogen is released from the holding tank, rapid cooling takes place and ice buildup could be a limiting factor in achieving the desired flow rate. To increase the flow rate, multiple tanks could be used in tandem. Another approach to maximize the flow rate of nitrogen to the MRDS could be to intermix air with nitrogen. If oxygen levels are low enough, fuel sources will not ignite and air (78% nitrogen and 21% oxygen) could substitute for a significant percentage of the gas requirement in place of using nitrogen for the total volume.

E.4 Mud System (Pumps, Pits, Shakers)

Drilling fluid, mud, is typically circulated through the bit and up the annulus to remove the cuttings from downhole, cool the bit, and clean the bit face. Mud pumps are typically positive-displacement, triplex pumps that circulate the drilling fluid throughout the system.

E.5 Auxiliary Electric Power

Auxiliary electric power at a drilling site is typically provided by stand-alone diesel-driven generators.

E.6 Cuttings Management

Depending upon the method of drilling, a cuttings management system must be deployed to contain the cuttings that are generated by the drilling process. For percussive drilling, these cuttings are sometimes combined with a water mist and dumped to a pit.

E.7 Directional Drilling Systems

Directional drilling technologies have improved substantially with the development of rotary steerable systems (RSSs). These systems are used with rotary drilling tools, primarily PDC bits, in sedimentary formations. A more common way to introduce directional drilling capabilities on shallow well drilling is to use a bent sub in the BHA that is directionally controlled from the surface by rotating the entire drill string. A motor is used below the bent sub to provide the preferred direction of drilling. Many positive displacement motors include an adjustable bend housing (ABH) (typically up to 6 degrees) that allows a prescribed offset to be introduced into the motor before it is tripped into the hole.

E.8 Casing Systems

Casing is set in a conventional drilling application by removing the bit and drill string from the hole and tripping in and welding the casing at each joint. This method is slow and cumbersome and not amenable to a rescue drilling situation. Other casing systems have been used, including fiberglass and plastic pipe. Percussive drilling systems feature an overburden drilling system that allows casing to be coincidentally run while drilling the pilot hole. One of these systems is Atlas Copco's Symmetrix Ring bit. Other overburden systems include Superjaws (Numa), Rotex , ODEX (Sandvik, Atlas Copco – Overburden Drilling with Eccentric Bit), and TUBEX. Casing while drilling systems also exist but these are cumbersome for a rescue drilling configuration.

Appendix F. Drilling Diagnostic Measurements and Control

Generally, completely autonomous drilling operations do not exist within the drilling industry. Most drilling applications usually have access to personnel to intervene in the drilling process, make supervisory decisions based upon measured data, and determine a course of action. Commercial drilling control systems are available that monitor some aspect of the drilling process and take actions, but these are limited in scope. The MRDS concept will rely upon an experienced operator controlling the drilling process. This will require that drilling conditions be monitored, data analysis be conducted to diagnose the state of the drilling process, and then a decision be made to modulate the operating conditions accordingly. An overall approach is discussed below and includes a description of the measurement types and an approach for development of sensor hardware and an accompanying diagnostics display system to interpret the data to improve the drilling process.

F.1 Drilling Diagnostics Measurements

A variety of drilling tools are available on the market to monitor drilling conditions. This includes measurement while drilling (MWD) and logging while drilling (LWD) tools. These tools sometimes include strain gage sections to monitor WOB (weight on bit) and torque. They also include accelerometers for triaxial acceleration monitoring and magnetometers for velocity monitoring. These data are monitored and recorded at a prespecified sampling rate. Some measurement tools include the capability to trigger a high-data-rate capture in the event of a dynamic event. Data are usually written to memory for download when the BHA (bore hole assembly) is tripped out of the hole to the surface. Alternatively, the data may be transmitted at a low data rate using mud pulse telemetry. In the rare case when a wireline is run within the drill string down to the tool, high-frequency data may be transmitted to the surface for processing. The drilling industry is developing wired pipe networks for jointed-pipe drill strings, but these networks have not been adopted for routine use in production drilling.

Surface instrumentation includes those measurements made on most drilling rigs. These include WOB, torque on bit (TOB), RPM, depth, and fluid pressure. These measurements allow drilling operators to know where they are in the hole and whether they are drilling optimally for the given drilling situation. To this set we add rate of penetration (ROP), which is simply change in depth divided by time. In more complicated or deeper drilling where some sense of direction is needed, various survey and steering instruments may be added. For MRDS deployments, navigating to a particular point in space will normally require the use of steering and survey equipment. In designs that do not integrate this information into the tool set, these steering and survey methods require extra time to complete during drilling. The use of a downhole instrumentation package can maximize the amount of time spent advancing the hole and increase accuracy over nonintegrated methodologies.

For drilling where coiled tubing is used (which can have an instrumentation cable within it) or wired pipe for jointed pipe drilling, the drilling system can support a downhole instrumentation system. The implementation of downhole WOB, TOB, RPM, magnetometer, and inclination allows the drilling personnel to track the progress of a drilling operation in a far more efficient way. The magnetometer and inclinometer data in real time allow for the calculation of position and when coupled with a downhole steering device allow for accurate positioning of the borehole. To be compatible with the MRDS concept, it is envisioned that that majority of measurements would be made through a sensor sub located on the surface - as described below.

F.2 Drilling Diagnostics Sub-Subsystem

During drilling operations, it is convenient to monitor drilling parameters both at the surface and downhole to provide insight into the drilling process. However, measurements are easier to make at the surface since the problem with telemetry through the drill stem is avoided. The drilling diagnostics sub-subsystem for the MRDS could potentially be a number of modules that are physically installed in the drilling system, between the top drive and the first joint of drill pipe, in a diagnostics sub that is amenable to mounting on the top drive of the drill rig. Installed in this position, the drilling sub is envisioned to contain all of the necessary equipment to measure the parameters important to successful drilling. Since the drilling sub is in the active drill string, wireless communications will be required to control the sub in real time. The wireless link will also have to convey all of the data gathered from the sub.

F.3 Drilling Advisory Subsystem

The drilling advisory subsystem is the data gathering and display subsystem. The subsystem gathers the data from the various subsystems, displays user selected data, and provides an interface to the Internet for both gathered data and incoming information. The drilling advisory system is intended to provide information to the driller so that the driller may choose to modulate operating conditions to improve the overall drilling process.

Appendix G. Transportation Options

Helicopters for cargo airlift are available both commercially and through the government. The National Guard would be the most likely governmental source of air transportation services (Figures G-1 through G-5). For Army involvement, a level of complexity is added in that a presidential order must be in place and in an emergency situation the Federal Emergency Management Agency (FEMA) also needs to be involved. Therefore, the National Guard is the recommended government resource. The National Guard can respond on a state level even though the vast majority of the National Guard is in federal status. Because most mines are operated by private entities, the antitrust law prevents the National Guard from competing with private industry. In most cases, if the state is willing to declare a state of emergency due to a mining accident, the National Guard's services can be called on and the antitrust law does not apply.

The National Guard's heaviest lifting helicopter is a variation of the Chinook (26,000 lbs lift capacity at sea level). Commercial services have similar capabilities to those of the National Guard; however, prior arrangements need to be made to ensure a medium- to heavy-lifting commercial helicopter will be available when needed.

Prior arrangement details with a commercial heavy-lift helicopter service include knowing cargo weights, rigging arrangements, commercial fleet carrying capacities, and helicopter availability. An ongoing contract with multiple services is advisable should one service have minimal services available at the time of a mine accident.

An additional consideration when choosing a commercial heavy-lift helicopter service should be whether the company is certified to transport people. The certification the commercial company must have is known as a Part 135 certificate. It is likely that injured miners would need to be airlifted from the rescue site to a convenient location for rapid transportation to a hospital. Using the same helicopter used to transport the MRDS equipment would simplify planning and likely reduce rescue operation costs.

Heavy equipment could be delivered close to the rescue site using a typical semitruck tractor trailer setup. The maximum gross weight for a semitruck is 80,000 lbs, which typically means a payload of about 45,000 lbs. Commercial construction equipment could then be used to drive up rough, steep, rutted, and narrow primitive roads. Ideally, the entire MRDS could be broken down into components that fit on standard size pallets. The pallets could then be unloaded from the semitruck with a forklift and onto the construction equipment that would drive it to the drill site. If no roads exist, an onsite assessment should be conducted to determine the time savings if air lifting is employed and/or new roads made for access above the underground mine accident.

Appendix H. Test Rig Development and Description

As noted, Sandia is currently performing technical development of high-speed DTHH (down-the-hole hammer) drilling technology with other federal funds that have been leveraged for application to development of MRDS system applications. The experimental capability described in this appendix was developed in its entirety on these other programs. The capability was made available for this project and is summarily described below.

H.1 Test Rig Development Design Goals

The experimental component of the project necessitated the development of an efficient high-pressure DTHH testing capability. User specifications for the system design considered the ability to meet estimated power and air requirements, the ability to drill hole depths at least four feet, expedient and controlled indexing of the drill head to enable rapid and optimal use of rock-specimen volume, adherence to environment, safety, and health (ES&H) requirements and a comprehensive sensor package to monitor and acquire relevant DTHH data.

The basic approach undertaken involves burying 4-foot cubes of rock in the ground with the top surface exposed at ground level for drilling. Rock specimens are buried to reduce the overall height needed for the rig mast to simplify and improve ergonomics by bringing the operation down to ground level and to improve overall safety of the operation by mitigating the effects of potential sidewall blowouts of the rock with earthen confinement. The drilling system is composed of three basic components. One is the drill rig that provides primary drilling functions of thrust force, translation of the drill bit into the rock and drill string rotation for bit indexing. The rig also possesses a cuttings diverter for containment and redirection of rock cutting and a side-to-side indexing capability for rapid movement of the drill head over fresh sections of rock. Rock cuttings are diverted to a stand-alone cyclone separator using a 6-inch hose. The second primary component of the system is a hydraulic power unit used to power the drill rig. Minimum requirements for this system are 45 gpm flow capacity at 3,000 psi system pressure. The third component of the system is the air compression package. The last component in particular significantly exceeds the performance characteristics of most commercial operations due to the uncharacteristically high pressures and flow rates used in the high-speed drilling application. The outlet of the air compression package is connected to the high-pressure swivel on the drill rig through a high-pressure hose.

H.2 Drill Rig Description

The drill rig is a customized design manufactured by TEI Rock Drills, a company specializing in the manufacture of limited-access rigs. Key rig specifications include the following:

- Thrust Force – 7,500 lbf
- Stroke – 6.5 feet
- Torque – 1,000 ft-lbf @ 3,000 psi
- Rotational Speed – 300 rpm (dependent on hydraulic power unit (HPU) flow output)
- Air swivel pressure rating – 2,500 psi

The rig also possesses a variety of other features designed to improve the safety and efficiency of testing:

- A built-in cuttings diverter at the base of the mast
- Four hydraulically adjustable leveling legs for alignment of the drill head with the rock
- A side traverse mechanism with four feet of stroke for indexing of the drill head to drill new holes
- A remote control stand with a 20-foot long umbilical

Concrete divider blocks are placed on structural members attached to the feet of the rig to provide the weight needed to the react thrust applied during drilling. Figure H-1 shows the design layout of the drill rig. Figures H-2 through H-5 are photos of the rig setup in the field.

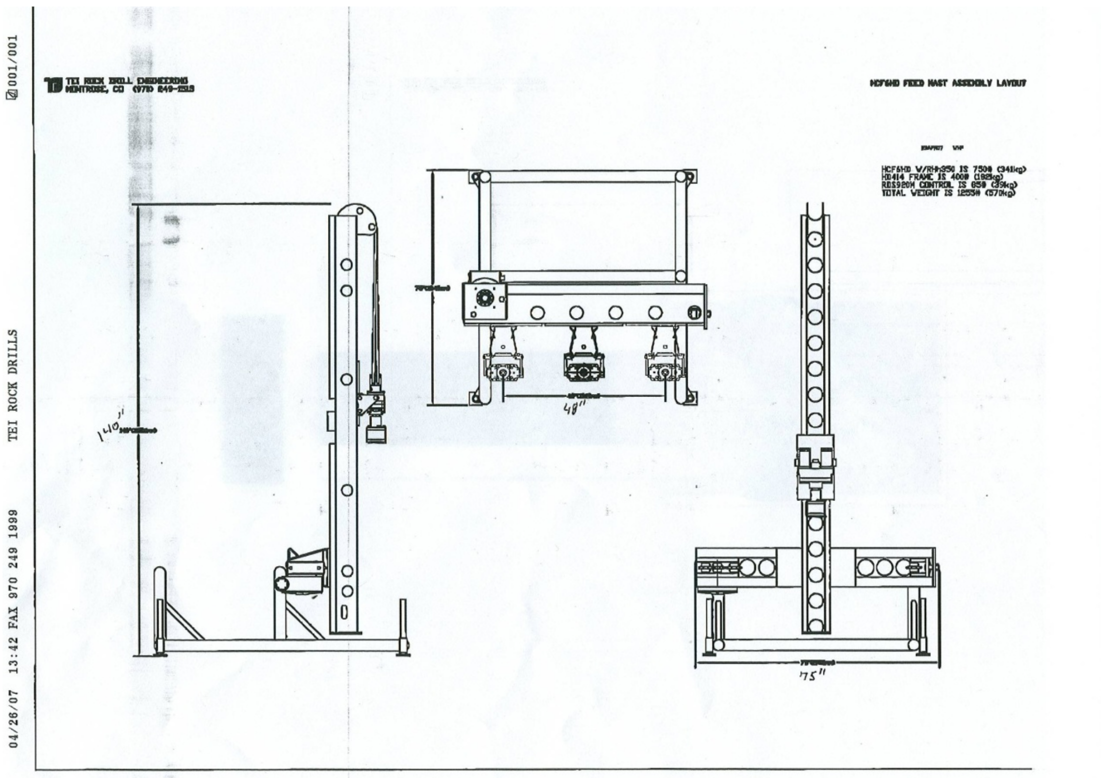


Figure H-1. Drill rig design layout.

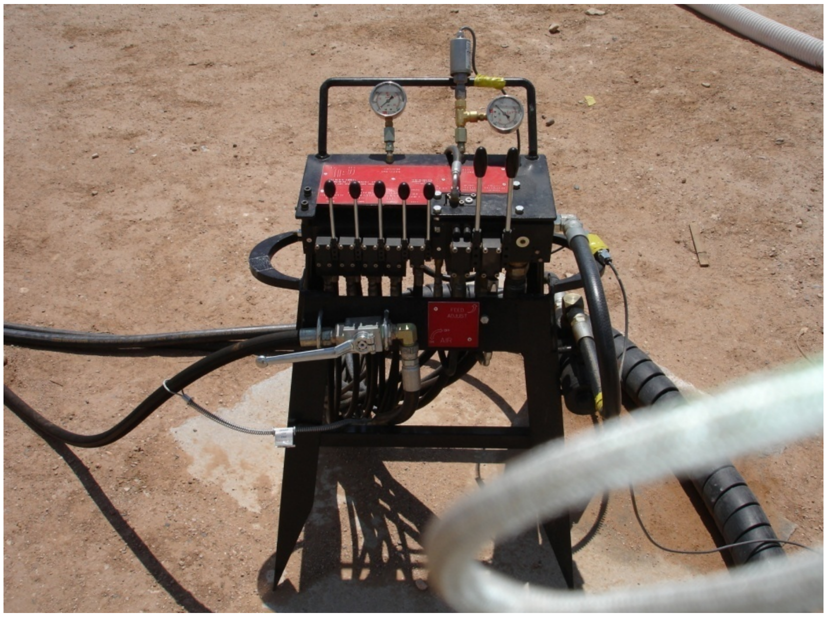


Figure H-2. Drill rig control stand.

Figure H-3a. Drill rig.

Figure H-3b. Drill rig.

Figure H-4. Rig cuttings diverter.

Figure H-5. Rotary head.

H.3 Air Compression System

The air pressures and flow rates required for the application are on the order of 1,500 psi and 3,500 scfm, respectively. A system capable of providing these rates on a continuous, persistent basis would require two to three lower-pressure compressors (350 psi–500 psi @ 1,000 scfm) feeding into a booster compressor. Because the quoted costs for such a system was over $500k, in excess of the project allotment for the test site, an alternative air-delivery system was developed based on the intermittent air supply needed to drill quarried rock specimens to depths of approximately four feet.

The configuration that was developed incorporates a high-pressure, lower-flow-rate compressor that feeds into an arrangement of 16 Department of Transportation (DOT) high-pressure gas storage bottles rated to 4,500 psi with approximately 190 gallons of wet storage volume. The system is housed in a portable building. The building includes a forced-air cooling system that meets compressor cooling requirements. The compressor has a rating of 50 scfm @ 5,000 psi but is limited to 4,500 psi output to conform with storage bottle limitations. The gas bottles are connected in parallel racks of eight. The two racks are "teed" to a common output that feeds into a high-pressure, high-flow regulator. The regulator is used to control the air pressure delivered to the hammer. A pressure relief valve downstream of the regulator is used to limit output pressure to 2,000 psi. The lowest component rating downstream of the regulator is currently 2,500 psi. A high-pressure lubrication pump line is also "teed" into the discharge line to provide lubricating oil to the DTHH. It should be noted that at these operational pressures, non-hydrocarbon-based lubricants must be used to avoid the possibility of autoignition of the lubricant. At full charge, the system has sufficient volume for a run time on the order of a minute and a half at 1,500 psi output. DTHH drilling tests at this pressure typically take between 10 and 30 seconds. Pictures of the system are shown in the figures below.

Figures H-6a and H-6b. Air compressor building.

Figures H-7a and H-7b. Storage bottle manifold.

Figure H-8. Lubrication pump housing.

Figure H-9. Discharge relief valve.

H.4 Hydraulic Power Unit

The hydraulic power unit (HPU) used to supply the rig control bank is a commercial-off-the-shelf (COTS) product manufactured by Hydra Tech. The HPU is of the diesel-prime-mover, swash-plate piston variety rated to 3,000 psi @ 44 gpm. A picture of the HPU is shown in Figure H-10.

Figure H-10. Hydraulic power unit.

H.5 System Instrumentation

The table below contains a list of sensors and the corresponding parameter measured by the system to characterize the drilling process.

Table H-1. Test Site Measurement Parameters

Sensor	Measurement Parameter
Feed cylinder pressure transducer	Weight on bit
Rotary head pressure transducer	Rotary head torque
Rotary head tachometer	Rotary head rpm
Rig accelerometer	DTHH blow frequency
Bottle rack pressure transducer	Bottle rack air pressure
Swivel pressure transducer	Swivel air pressure
Feed system wire potentiometer	ROP

Appendix I. DTHH Thermodynamic Model Development

This appendix describes the theoretical formulation and basic algorithmic procedures used to develop simulation tools for DTHH operation. As noted, Sandia is currently performing technical development of high-speed DTHH drilling technology with other federal funds that have been leveraged for application to development of MRDS system applications. The modeling capability described in this appendix was developed in its entirety on these other programs. The capability was made available for this project and is summarily described below.

DTHH thermodynamic model theoretical formulation

Reference model geometry

As an initial step in the analysis, consider the simplified, reference, geometry shown in Figure I-1. This geometry is introduced solely as a reference for development of the mathematical relations that describe the behavior of a gas contained within a volume that is allowed to compress and expand in response to the action of a piston. In addition, inflow and outflow are allowed during the compression and expansion processes. In this arrangement, a piston of mass *m* is free to move in a cylindrical chamber of cross-sectional area *A*. Flow from an external source can enter through port *1* and flow can exit through port *2*. The position of the piston is given by the coordinate *x*. Within the open volume, *V*, the pressure, temperature, and density are denoted by *p*, *T*, and ρ, respectively. The conservation of energy for the volume is expressed by

$$\frac{dQ}{dt} = \frac{dU}{dt} + \frac{dW}{dt}, \qquad \text{I-1}$$

where the terms represent, from left to right, the rate of heat addition, the rate of change of internal energy, and the rate at which work is done by the volume on the surroundings.

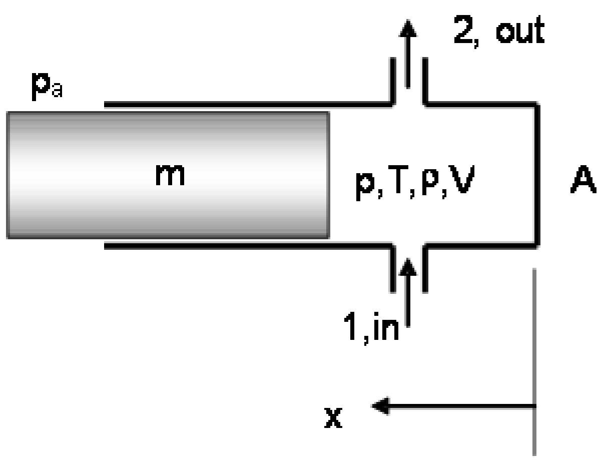


Figure I-1. Reference geometry for hammer drill model.

Equation I-1 can be expressed in integral form as

$$\frac{dQ}{dt} = \frac{d}{dt}\int_{Volume} e\rho dV + \int_{Area} (h + \frac{v^2}{2} + gz)\rho \underset{\sim}{v} \cdot d\underset{\sim}{A} + \frac{dW}{dt}, \qquad \text{I-2}$$

where $e = u + v^2/2 + gz$, $h = u + p/\rho$, $du = c_V dT$, $dh = c_P dT$, $c_P - c_V = R$, $k = c_P/c_V$, and the perfect gas law

$$p = \rho RT \qquad \text{I-3}$$

is assumed to apply. The conservation of mass relation

$$\frac{d}{dt}(\rho V) = G_{in} - G_{out} \qquad \text{I-4}$$

and the equation of motion for the piston

$$m\frac{d^2x}{dt^2} = A(p - p_a) - c_\mu \frac{dx}{dt} \qquad \text{I-5}$$

complete the equations required to completely describe the behavior of the system. In the above, the mass flow rates into and out of the volume are, respectively, G_{in} and G_{out}, the *a*-subscript represents conditions at the back of the piston, and c_μ is a dimensional coefficient of friction (units: force/velocity).

It is now desired to combine the foregoing relations into a convenient form for analysis (Chiang and Stamm1998; Yu et al. 1966). The time derivative of the perfect gas law yields

$$\frac{dp}{dt} = R\rho\frac{dT}{dt} + RT\frac{d\rho}{dt}. \qquad \text{I-6}$$

If the process is assumed adiabatic and the kinetic energy terms are neglected, then Eqn. I-2 can be written as

$$0 = \frac{d}{dt}\left(\rho uV\right) + hG_{out} - h_{in}G_{in} + p\frac{dV}{dt}, \qquad \text{I-7}$$

where the subscript *in* refers to conditions for the entering flow that originates from an external source. The combination of Eqns I-6 and I-7 then results in

$$\frac{dp}{dt} = \frac{kp}{V}\left[\frac{R}{p}\left(G_{in}T_{in} - G_{out}T\right) - \frac{dV}{dt}\right]. \qquad \text{I-8}$$

If Eqn. I-4 is solved for $\frac{d\rho}{dt}$ and substituted into I-6, a relation for $\frac{dT}{dt}$ can be obtained that involves the term $\frac{dp}{dt}$. Substitution for $\frac{dp}{dt}$ from Eqn I-8 then yields

$$\frac{dT}{dt} = \frac{T}{V}\left\{\frac{R}{p}\left[G_{in}\left(kT_{in} - T\right) - TG_{out}\left(k-1\right)\right] - \left(k-1\right)\frac{dV}{dt}\right\}. \qquad \text{I-9}$$

Since the volume displaced can be related to the position of the piston by $dV = Adx$, the volume and its derivative in the prior relations can be expressed in terms of the piston position and velocity.

The relations developed to this point can be combined into a system of first-order ordinary differential equations (ODEs) for the description of the piston dynamics. In addition to the basic relations, auxiliary relations are required to model the flow to and from the volume and to represent the impact of the piston on the drill bit. To represent the flow into and out of the volume, it is assumed that flow is through a restriction that can be represented as an orifice. Two approaches for the representation of this process are considered: a standard orifice model and a compressible flow model. Computations can be performed with either the standard or compressible orifice flow options.

<u>Standard orifice model</u>

The mass flow can be predicted through use of an orifice model and will be of the forms (Crane Co. 1991)

$$G_{in} = C_{in}A_{T_{in}}\sqrt{\rho_0(p_0 - p)} \text{ and } G_{out} = C_{out}A_{T_{out}}\sqrt{\rho(p - p_0)}\ , \qquad \text{I-10}$$

where the *0*-subscript references stagnation conditions in the reservoir from which the flow is initiated, *C* is an orifice coefficient, and A_T is the effective throat area of the orifice. In general, the orifice coefficient and effective throat area depend on the flow direction. Hence, the entering flow is assumed to originate from an external source, and the exiting flow originates from the contained volume *V*. This approximation does not account explicitly for compressibility effects. When compressibility is important, this effect can be accommodated to some extent through an appropriate choice for the orifice coefficient. This approach does not take into account the phenomenon of choking of the flow through the orifice.

Compressible flow model

The mass flow rate G_{in} into a volume from a reservoir through a converging passage for compressible, isentropic, flow is

$$G_{in} = C_{in}\sqrt{\frac{k}{RT_0}}\,p_0 A_{T_{in}} M\left(1+\frac{k-1}{2}M^2\right)^{-(k+1)/2(k-1)}, \qquad \text{I-11}$$

where the Mach number M is given in terms of the pressure ratio by

$$M = \sqrt{\frac{2}{k-1}}\left[\left(\frac{p_0}{p}\right)^{(k-1)/k} - 1\right]^{1/2}, \qquad \text{I-12}$$

the pressure p is the local pressure at the cross-sectional area $A_{T_{in}}$, and C_{in} is an orifice coefficient that can be used to represent conditions that differ from ideal. When the flow is subsonic, the pressure p is equal to the downstream pressure. The Mach number is unity at $A_{T_{in}}$ when the local pressure ratio is

$$\frac{p}{p_0} = \left(\frac{2}{k+1}\right)^{k/(k-1)}. \qquad \text{I-13}$$

For $k = 1.4$, Eqn. I-13 yields 0.528 for the pressure ratio, corresponding to "choked flow." When the pressure ratio across a convergent passage is less than the "critical" value given in Eqn. I-13, the pressure at the exit area remains fixed at the critical value. For this example, stagnation conditions are taken as those in the external reservoir when flow is directed into the volume. When flow occurs from the volume, the conditions within the volume are identified with the stagnation conditions. The orifice coefficient and throat area can depend on the direction of flow, as indicated above in the description of the standard orifice model.

Hammer drill

In Figure I-2, a sketch is presented that is assumed typical of a hammer drill and includes notation used in the development of the mathematical model for the hammer drill. The volumes V_1, the power chamber, and V_2, the return chamber, are connected periodically to a high-pressure reservoir through an opening in the feed tube. The volumes are also exhausted periodically to the borehole through an exhaust tube and flow passages in the bit. Connections to the volumes from the reservoir and borehole are through machined passages in the piston and the housing. We recognize that the design details of a hammer drill can vary and have thus attempted to develop a general model that can be modified to accommodate a variety of configurations. In the remainder of this section, we present a mathematical model for the hammer drill, based on the illustration in Fig. I-2.

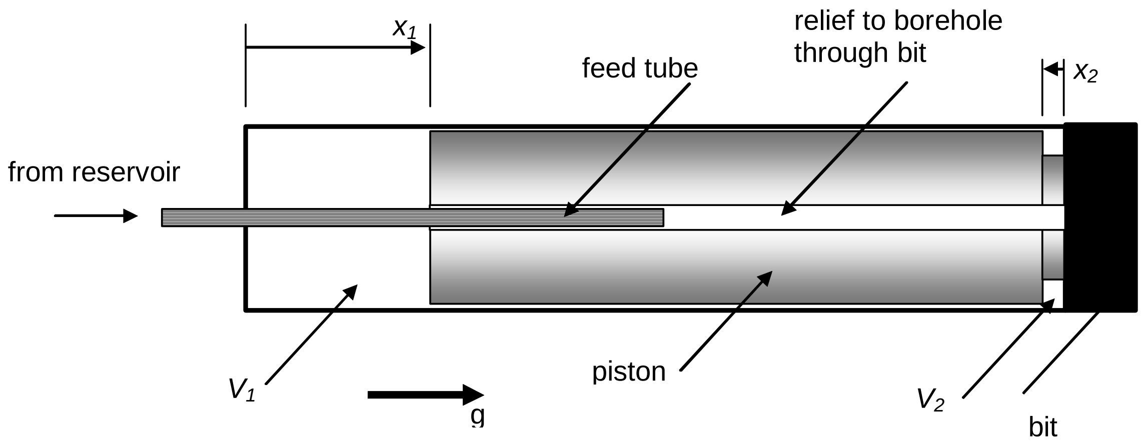


Figure I-2. Schematic of hammer drill.

System of equations

The system of ODEs that describe the hammer drill dynamics are developed from Eqns. I-1 through I-9. There are two volumes associated with the hammer drill illustrated in Figure I-2. Volume 1 is the region above the piston, and volume 2 is immediately above the bit. If x_1 is the length associated with volume 1 and x_2 is the length associated with volume 2, then the time variations of these quantities are

$$\frac{dx_1}{dt} = \dot{x}_1 \ , \tag{I-14}$$

$$\frac{d\dot{x}_1}{dt} = \frac{1}{m}\left(A_1 p_1 - A_2 p_2\right) - c_\mu \dot{x}_1 + g \ , \tag{I-15}$$

$$\frac{dx_2}{dt} = -\dot{x}_1 \ , \tag{I-16}$$

where t is time, m is the mass of the piston, $A_n p_n$ are the products of area and pressure in volumes 1–2 ($n = 1, 2$), g is the acceleration of gravity, c_μ is a friction coefficient, and a superposed dot indicates a time derivative, e.g., $\dot{x}_1$ is the piston velocity. For generality, it is assumed that both volumes 1 and 2 can communicate with either a high-pressure reservoir or an external borehole and that flow can proceed either into or out of the respective volume from either the reservoir or the borehole. Hence, the following eight possible flows are defined: $G_{1iR}, G_{1oR}, G_{1iB}, G_{1oB}, G_{2iR}, G_{2oR}, G_{2iB}, G_{2oB}$, where the subscript refers to the volume (1,2), the flow direction (*i* = into volume, *o* = out of volume), and the external region (*R* = reservoir, *B* = borehole). Thus, for example, G_{1iR} represents flow into volume 1 from the high-pressure reservoir. The time variations of pressures p_1 and p_2 are then

$$\frac{dp_1}{dt}=\frac{kR}{(A_1x_1+V_1)}\left[T_RG_{1iR}+T_BG_{1iB}-T_1(G_{1oR}+G_{1oB})-\frac{p_1}{R}A_1\dot{x}_1\right] , \qquad \text{I-17}$$

$$\frac{dp_2}{dt}=\frac{kR}{(A_2x_2+V_2)}\left[T_RG_{2iR}+T_BG_{2iB}-T_2(G_{2oR}+G_{2oB})-\frac{p_2}{R}A_2\dot{x}_2\right] , \qquad \text{I-18}$$

where V_1 and V_2 represent stationary (i.e., unchanging) volumes in the two chambers. These volumes consist of features such as cutouts in the case and piston and the void between the piston nose and the bit when the piston is seated against the bit shank (see Figure I-2) which do not change as the piston moves.

The variations of temperatures in volumes 1 and 2 are given by

$$\frac{dT_1}{dt}=\frac{T_1}{(A_1x_1+V_1)}\left\{\frac{R}{p_1}\left[\left(kT_R-T_1\right)G_{1iR}+\left(kT_B-T_1\right)G_{1iB}-T_1(k-1)\left(G_{1oR}+G_{1oB}\right)\right]-\left(k-1\right)A_1\dot{x}_1\right\} , \qquad \text{I-19}$$

$$\frac{dT_2}{dt}=\frac{T_2}{(A_2x_2+V_2)}\left\{\frac{R}{p_2}\left[\left(kT_R-T_2\right)G_{2iR}+\left(kT_B-T_2\right)G_{2iB}-T_2(k-1)\left(G_{2oR}+G_{2oB}\right)\right]-\left(k-1\right)A_2\dot{x}_2\right\} . , \qquad \text{I-20}$$

When required, densities are obtained from the perfect gas law, Eqn. I-3.

Hence, Eqns. I-14 through I-20 constitute a system of seven first-order ODEs for the 7 unknowns: $x_1, \dot{x}_1, x_2, p_1, p_2, T_1, T_2$. For future reference, these unknowns are numbered consecutively from 1 through 7, respectively. In addition to the seven ODEs identified, various physical dimensions and quantities must be specified along with the reservoir pressure and temperature $\left(p_R, T_R\right)$ and the borehole pressure and temperature $\left(p_B, T_B\right)$. To initiate the numerical solution of the set of ODEs, initial conditions must be specified for all quantities. The specific values for initial conditions are not crucial since only the steady-state response of the hammer drill is of concern. The initial conditions should, however, be physically realistic. Two remaining processes that must be considered are the flows through the various orifices that communicate with the piston and the impact of the piston with the drill bit. These processes are considered in the following two sections.

Standard orifice model

With reference to Eqn. I-10, the mass flow rates as obtained from orifice flow considerations are

$$
\begin{aligned}
G_{jiR} &= C_{jiR} A_{T_{jiR}} \sqrt{\rho_R (p_R - p_j)} \\
G_{joR} &= C_{joR} A_{T_{joR}} \sqrt{\rho_j (p_j - p_R)} \\
G_{jiB} &= C_{jiB} A_{T_{jiB}} \sqrt{\rho_B (p_B - p_j)} \\
G_{joB} &= C_{joB} A_{T_{joB}} \sqrt{\rho_j (p_j - p_B)}
\end{aligned} \quad , \qquad \text{I-21}
$$

where $j = 1, 2$ indicates the volume. These relations are valid when compressibility effects are negligible. Some effects of compressibility can, however, be accommodated by modification of the orifice coefficients. The orifice throat areas and coefficients are associated with the openings between volumes 1 and 2 and the respective reservoirs with which they communicate. Hence, eqns. I-21 encompasses eight flow configurations. To simplify the analysis, it will be assumed that the orifice coefficient and throat area are unchanged for inflow, regardless of whether the flow is from the reservoir or borehole. A similar assumption is assumed to apply to outflows.

Compressible flow model
The compressible flow option is outlined in Eqns. I-11 through I-13. The mass flow rates for flow between the volumes and the high-pressure reservoir are thus given by

$$
G_{jiR} = C_{jiR} \sqrt{\frac{k}{RT_R}} p_R A_{T_{jiR}} M \left(1 + \frac{k-1}{2} M^2\right)^{-(k+1)/2(k-1)} , \qquad \text{I-22}
$$

where

$$
M = \sqrt{\frac{2}{k-1}} \left[\left(\frac{p_R}{p_j} \right)^{(k-1)/k} - 1 \right]^{1/2} , \qquad \text{I-23}
$$

and

$$
G_{joR} = C_{joR} \sqrt{\frac{k}{RT_j}} p_j A_{T_{joR}} M \left(1 + \frac{k-1}{2} M^2\right)^{-(k+1)/2(k-1)} , \qquad \text{I-24}
$$

where

$$
M = \sqrt{\frac{2}{k-1}} \left[\left(\frac{p_j}{p_R} \right)^{(k-1)/k} - 1 \right]^{1/2} . \qquad \text{I-25}
$$

When the flow is choked, the Mach number is unity at the throat, and the mass flow rates are

$$G_{jiR} = C_{jiR}\sqrt{\frac{k}{RT_R}}p_R A_{T_{jiR}}\left(\frac{2}{k+1}\right)^{(k+1)/2(k-1)}$$
$$G_{joR} = C_{joR}\sqrt{\frac{k}{RT_j}}p_j A_{T_{joR}}\left(\frac{2}{k+1}\right)^{(k+1)/2(k-1)} , \qquad \text{I-26}$$

where $j = 1,2$ and a similar set of relations apply to flows associated with the borehole. These relations are obtained upon replacing *R* with *B* in the relations presented. As for the standard orifice model, there are eight possible flow configurations. When the orifice coefficient and throat area are not dependent on the direction of flow, there are four possible flow configurations.

Pressure developed through bit exhaust porting to borehole
The dependence of nonchoked mass flow using the standard orifice model on both downstream and upstream pressures necessitates the development and incorporation of additional relationships to account for pressure developed within the bit bore during exhaust of the hammer chambers to the borehole. If air flow through the bit exhaust tube and bore is subsonic, downstream pressure is assumed to be equal to borehole pressure. A sufficiently high mass flow rate through the bit bore, on the other hand, will result in a choked flow condition that will produce an additional back pressure that must be factored into the model for the standard orifice flow calculations. The current formulation of the model neglects effects associated with cuttings removal and the flow of air past the bit junk slots (flow passages around the periphery of the bit).

The use of a relationship to calculate bit bore pressure is conditional based on the calculated velocity of the flow stream for the prescribed borehole pressure. Downstream pressure calculation occurs if

$$v_b = \frac{G_{joB}}{\rho_B A_b} > c , \qquad \text{I-27}$$

where v_b is the gas velocity through the bit, G_{joB} is the exhaust mass flow rate through the bit to the borehole, either for a previous time step or for an averaged time interval, ρ_B is the prescribed borehole gas density, A_b is the limiting area through the bit bore and c is the sonic velocity of the gas.

If the calculated velocity of the gas through the bit bore exceeds the sonic velocity, then back pressure or downstream pressure is calculated using the assumption that gas velocity cannot exceed sonic. The expression for total pressure is

$$p_b = \rho_B (RT + \frac{1}{2}c^2) \cdot \qquad \text{I-28}$$

The density term in this relation is obtained using either instantaneous or averaged mass flow rates from previous time steps yielding the expression

$$p_b = \frac{G_{jOB}}{A_b c}(RT + \frac{1}{2}c^2) \cdot \qquad \text{I-29}$$

Leakage flow between volumes
The slidable piston within the hammer does not incorporate any pressure-tight sealing features. Connectivity between volume 1, volume 2, and the borehole is therefore dictated by the dimensional tolerances of the parts within the hammer. For example, the radial clearance between the bit exhaust valve and the piston inner diameter is on the order of 0.005 inch. This clearance provides a leak path from volume 2 to the borehole when volume 2 is disconnected from the borehole. Numerous other leak paths can be accounted in the formulation and are in general dependent on the geometric configuration of the hammer. Leakage flows are calculated using either Eqn. I-21 or I-26 using conditional statements comparing chamber pressures to determine the direction of flow.

<u>Piston impact with drill bit</u>
The simplest representation of the impact between the piston and the drill bit is obtained through momentum and energy considerations. Take the mass of the drill bit as m_B and the mass of the piston as m. The initial velocity of the drill bit is zero, and the initial velocity of the piston is v_i. It is required to determine the velocities of the piston v_f and drill bit u_B after impact. The coefficient of restitution e is defined by

$$v_f - u_B = -ev_i \qquad \text{I-30}$$

and is representative of the energy conservation during impact; a coefficient of restitution of unity corresponding to conservation of kinetic energy. The conservation of momentum requires

$$mv_i = mv_f + m_B u_B , \qquad \text{I-31}$$

Simultaneous solution of Eqns. I-30 and I-31 and provides

$$v_f = v_i\left(\frac{m - em_B}{m + m_B}\right) \quad u_B = v_i\left[\frac{m(1+e)}{m + m_B}\right] . \qquad \text{I-32}$$

Two observations can be made that support the results obtained. First, if the two masses are of equal magnitude and the coefficient of restitution is unity, then the final velocity of the piston is zero, and all the kinetic energy of the piston is imparted to the drill bit. If, however, the drill bit in contact with the material being drilled is represented by a mass that is larger than the mass of the piston, the piston rebounds with a velocity opposite in direction to the initial velocity; the magnitude of which depends on the masses and coefficient of restitution. For reference, the impulse imparted to the bit is

$$I = \frac{v_i m m_B (1+e)}{m_B + m} . \qquad \text{I-33}$$

Estimates for the coefficient of restitution will also depend on the dynamics of the interaction between the drill bit and the rock being drilled (Chiang and Elias 2000). In practice, this coefficient is estimated to be approximately 0.3. The influence of the coefficient of restitution is also accounted for in the calculation of the power delivered to the rock using conservation-of-energy considerations. The energy delivered to the rock is thus the difference of the kinetic energy of the piston prior to impact and its return energy immediately after impact. Power is then calculated as

$$Power = \frac{1}{2}(1-e^2)mv_i^2 f \quad \text{,} \qquad \text{I-34}$$

where *f* is the hammer blow frequency.

Sequence of hammer drill operation events

With reference to Figure I-2, a sequence of events can be identified that characterizes the operation of the hammer drill with respect to flow in or out of the two hammer-chamber volumes. Although somewhat tedious, this level of detail is required to develop a correct modeling strategy and hence to produce a reasonable prediction of the hammer drill operation. The critical events defined in Table I-1 are given in terms of a reference position of the piston during its stroke for a typical valveless hammer configuration.

Table I-1. Sequence of events and corresponding piston positions for hammer drill operation

Position	Event Description
x_{psc1}	Power chamber rear pressure supply close position
x_{psc2}	Power chamber forward pressure supply close position
x_{peo}	Power chamber exhaust open position
x_{reo}	Return chamber exhaust open position
x_{rso}	Return chamber supply open position

With reference to Table I-1, the sequence of events is as follow:

1. $x_1 < x_{psc1:}$ No flow in or out of power chamber from reservoir or borehole
2. $x_{psc1} < x1 < x_{psc2}$: Flow from reservoir into power chamber
3. $x_{psc2} < x_1 < x_{peo}$: No flow in or out of power chamber from reservoir or borehole
4. $x_1 > x_{peo}$: Flow from power chamber to borehole
5. $x_1 < x_{reo}$: Flow from return chamber to borehole
6. $x_{reo} < x_1 < x_{rso}$: No flow in or out of return chamber from reservoir or borehole
7. $x_1 > x_{rso}$: Flow from reservoir to return chamber

Events 1 through 7 also include leakage calculations associated with clearances between hammer parts and the resultant flow paths between chambers and between the return chamber and the hammer exhaust tube. As mentioned previously, these flow paths are dependent on the geometry of the hammer configuration modeled.

Appendix J. Hammer Bit Development and Verification

J.1 Introduction

Bit performance is an important consideration in the overall development of a DTHH (down-the-hole hammer). The hammer and bit must work together as an engineered system to meet the stated drilling objectives. Accordingly, the bit must be appropriately designed for these requirements. This is especially important for the NIOSH MRDS because the bit must be aggressive to realize rate-of-penetration requirements and robust to ensure drilling to the required depths.

J.1.1 DTHH Bit Principle of Operation

Hammer bits rely upon transmission of kinetic energy from the hammer piston to the bit to penetrate the formation. This energy transmission process must be as efficient as possible to maximize the rock penetration and removal with each impact from the piston on the bit shank. The parameters governing this performance are introduced here. An isometric view of a hammer bit with the key features identified is shown in Figure J-1. The distribution of the buttons across the face of the bit forms the cutting structure of the bit. Generally, the buttons have a sharp point that allows them to penetrate the formation with each successive blow from the hammer piston. The bit is incrementally rotated to facilitate removal of the rock cuttings generated by the penetration and to index the bit over fresh rock for the subsequent penetration. The nozzles in the bit face direct the exhaust air stream from the hammer across the bit face to flush the cuttings away from the rock surface.

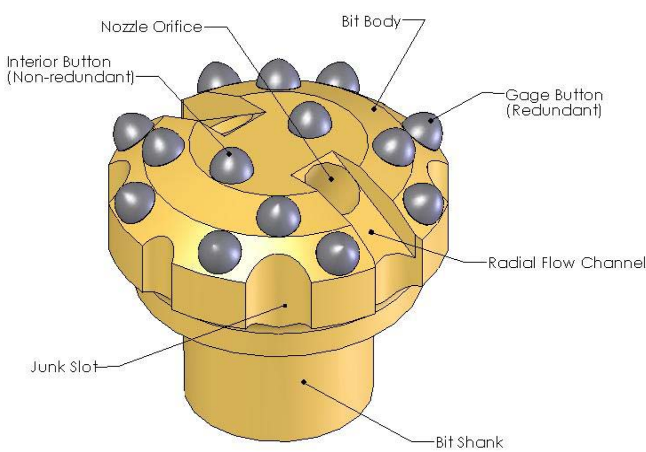


Figure J-1. Typical Hammer Bit.

J.1.2 Rock Bit Interaction Overview

The interaction between the cutting structure of the bit and the rock must address several considerations. Each of the indenters, or buttons, should penetrate new rock with each cycle of the hammer. The interaction between these buttons and the rock will determine the penetration-rate response of the bit for a given energy input to the hammer. This is a complex process that is dependent upon the rock properties, the button material and its geometric size and shape, and the operating conditions driving the bit into the rock. Ideally, the force penetration relationship could be known to help predict the performance of a bit. Experimentally, one could understand the relationship between penetration depth and input energy for a single button in a known rock type under very precisely controlled conditions. However, the complex cutting structures that compose a conventional bit make this accounting practically impossible for all the buttons that constitute the cutting structure. As the buttons interact with the rock, they will undoubtedly overlap previous button-rock interaction patterns that complicate a theoretical understanding of this relationship. Nevertheless, it is imperative that progress be made toward understanding this interaction phenomenon to improve the state of the art of existing hammer bit technology for the MRDS drilling objectives.

J.2 Development and Verification Approach

In the absence of theoretical relationships between bit design features and resulting response, an experimental program was pursued to determine the bit designs. As with the hammer development, a comprehensive approach was followed to develop hammer bit technology for the MRDS program. The approach began with a review of previous research on hammer bit performance. The literature review did not provide information pertaining to the penetration-rate response expected for the wide variety of bit designs conceivable in different rock types and hammer operating conditions. An experimental-based program was required to discern the preferred relationships.

The bit development approach consisted of testing conventional bits, developing and testing custom bits to address bit parameter variations, and then developing bits to be compatible with high-performance hammers.

J.3 DTHH Bit Design Considerations

Several DTHH bit design features govern the response of a given bit. Some of these features pertain to individual button characteristics, and some relate to integrated bit behavior. The features are discussed below.

J.3.1 Button Design Features

A number of button design features compose the specification of the bit-cutting structure.

- Button Profile - The inserts on a hammer bit vary in shape. A variety of profiles are presently used in industry, including ballistic, hemispherical, and conical profiles. The profile of the leading edge of the button determines the active area of the button while it penetrates the rock. Generally, conically shaped buttons are more aggressive because they have a smaller projected area than hemispherical buttons for a given penetration depth. However, buttons with a more conical-type profile will remove less volume per penetration. Conversely, hemispherical buttons offer greater volumetric removal but are less aggressive. Ballistic buttons provide a balance between aggressiveness and volume removal.
- Button Size – Button diameter influences the penetration per blow since it governs the effective bit area as the bit penetrates the formation. However, the entire frontal area of the bit must be removed so a balance is achieved between a large number of small buttons and a lesser number of large buttons. This relates to the volume of removal per

penetration and the extent of the damage surrounding the individual buttons with each impact.

- Button Materials – Buttons are normally fabricated from tungsten carbide. Polycrystalline diamond may be used for rock formations that are so abrasive that they cause the button profile to degrade with drilling depth.

J.3.2 Bit Design Features

- Button Density - The button count will determine the aggressiveness of the bit given that the effective area of the bit depends upon the number of buttons. The greater the number of buttons, the larger the area, and hence the less the penetration per blow. On the other hand, too few buttons will result in inadequate coverage.
- Button Distribution - Conceptually, the buttons can be distributed across the bit face using a variety of methodologies. The prevailing approach in industry is to use a symmetric distribution to balance the button forces. Other button layout approaches could include addressing the mechanical work performed per button, the mechanical load per button, or the specific energy per button. The buttons must be distributed to ensure adequate coverage so that the buttons engage the formation, and not the bit face, as the buttons create stress concentrations within the rock that improve the penetration rate.
- Redundant / Nonredundant buttons – One button-distribution approach locates the buttons in “tracks,” resulting in redundancy along a particular radial location. However, the inner radii of the bit are difficult to cover with redundant buttons because the circumference of a track becomes proportionally shorter with decreasing radius. For very high penetration rates, the bit face could actually come into contact with the rock on these inner radii if the bit advances sufficiently between button passes. The tracks with more button redundancy will have a larger allowable depth of cut before the face of the bit contacts the rock, as illustrated in Figure J-2. The interior buttons have little or no redundancy as a consequence of the geometric limitations on the interior radii of the bit. By contrast, the exterior buttons can be largely redundant.

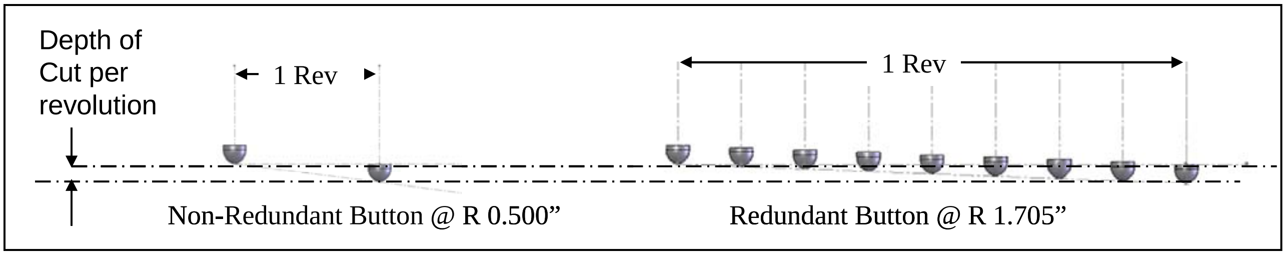


Figure J-2. Comparison of depth of cut per button for one nonredundant button (left) and eight redundant buttons (right)

- Gage Buttons – The gage buttons are important as they maintain the gage of the hole. If the gage buttons are reasonably redundant, this will reduce the individual button loads, and ensure they do not experience excessive wear.
- Bit Profile – Like the button profile, the profile of the bit face can determine the aggressiveness of the overall bit as it defines the presentation of the buttons to the rock.

- Bit Mass - The bit mass must be appropriately chosen in relation to the hammer piston dynamics to maximize the momentum transfer from the piston to the bit. Maximum momentum transfer from the piston to the bit will increase the bit penetration per impact.
- Bit Centerline – Some industry standard DTHH bits do not have buttons located on the centerline of the bit due to a history of problems with mechanical failures in this region. However, without sufficient coverage, the centerline of the bit could potentially contact the rock, reducing the stress concentration transmitted through the buttons. This is illustrated in Figure J-3.

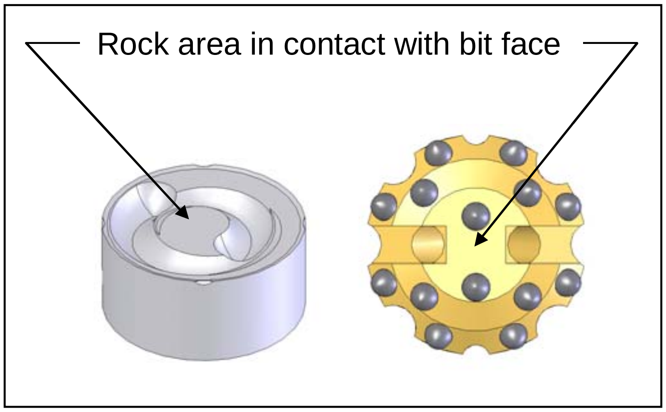


Figure J-3. Bottom hole pattern created in rock by centerline of bit face and two interior buttons.

- Nozzle Conditions – Appropriate nozzle hydraulic conditions are necessary to ensure clearing debris from the rock-bit interface to maintain a high stress concentration between the buttons and the rock. Nozzle conditions must also reduce the back pressure on the hammer exhaust to allow maximum energy delivery to the piston and the bit.
- Bit Cleaning - Good airflow across the bit face up through the junk slots is vital to maintain good bit cleaning to avoid the regrinding of cuttings. The junk slots should be as large as possible for this purpose. A high-pressure drop across the junk slot can also increase the back pressure on the hammer operation, reducing the net energy transfer to the bit.

J.4 Operating Parameters

A given DTHH bit design must be operated at particular drilling parameters for optimal performance. Some of these operating parameters, such as input pressure and rotational speed, are controlled directly. Some parameters are measured from the bit response. Other parameters are derived based upon a variety of governing parameters. These other parameters are discussed below.

J.4.1 Input Parameters

- Pressure, p [psi] - The input pressure to the hammer determines the cycle frequency for the piston and the impact energy delivered to the bit.

- Rotary Speed, N [rev/min or RPM] – The rotational speed of the bit can be selected independently of the hammer-cycle frequency. The rotary speed can be increased or decreased at a given input pressure to adjust the button advance between impacts.
- Weight-On-Bit, WOB [lb] – The thrust load applied to the bit can also be regulated independently from the pressure and rotary speed controls. Ideally, the bit should be operated at the minimum required thrust load to produce the maximum penetration rate.

J.4.2 Measured Parameters

- Impact Frequency, f [Hz] – A given hammer design will operate at a specific frequency for a given input pressure. It cannot be controlled independently of the pressure input.
- Rate of Penetration, ROP [ft/hr] – The ROP is a measure of the rate of advance of the bit into the rock.
- Reactive Torque, T [ft-lb] – A hammer bit is rotated to index the buttons to an area of un-penetrated rock. The reactive torque is a measure of the resistance exerted by the formation on the bit and must be overcome to increment the bit to the next impact position.

J.4.3 Derived Parameters

Several parameters are indicative of the bit performance and are calculated based upon the observed bit response.

- Depth of Cut per Revolution, doc [in/rev] - The ratio of the ROP (rate of penetration) to the rotary speed (N) is a measure of how far the bit advances into the rock in a single revolution. This parameter is useful as a measure of the advance rate of the bit relative to its cutting structure. The bit cannot advance more in a single revolution than the protrusion of any nonredundant button track on the bit face; otherwise, the bit face will come into contact with the formation.

$$\delta = doc = \frac{\mathrm{R}OP}{N}$$

- Blows per Revolution, bpr [blow/rev] – The ratio of the impact frequency to the rotary speed (f/N) determines the number of piston impacts per revolution of the bit. The number of blows per revolution for various piston-cycle frequencies measured during the advanced hammer development program is shown in Figure J-4 as a function of rotary speed.

$$\mathrm{bpr} = \left(\frac{\mathrm{f}}{\mathrm{N}}\right)$$

- Penetration per Blow, ppb [in/blow] – The ratio of the depth of cut to the number of blows per revolution yields an average value of how far the bit advances into the rock with each hammer cycle.

$$\text{ppb} = (\frac{\text{doc}}{\text{bpr}}) = \frac{(\text{ROP/N})}{(\text{f/N})} = \frac{\text{ROP}}{\text{f}}$$

- Arc Length, s [in] – The arc length advanced by a particular button depends upon the rotary speed and the radial position. The arc length as a function of blows per revolution is shown in Figure J-5. This is a useful parameter to monitor relative to the button diameter since each button must increment over to impact new rock with each successive piston impact. The plot shows that the interior radii advance far less than those more radially outward. Hence, the buttons on the interior do not need to be as redundant because they will not advance as much circumferentially with each hammer cycle.

- Energy per Blow, E_P [ft-lb or Joules] – The energy transmitted to the bit per impact is determined using the thermodynamic model. The impact energy transmitted to the bit depends upon the kinetic energy in the piston mass at impact, adjusted for a transmission efficiency that considers the return velocity of the piston (see the thermodynamic model section for additional detail).

$$\text{E}_P = \frac{1}{2} m_p v_s^2 \cdot T_R$$

  where m_p is the piston mass, v_s is the piston strike velocity, and T_R is the energy transmission efficiency of the piston.

- Hammer Power, P [hp or Watts] –The maximum power delivered by the hammer piston is predicted using the thermodynamic model. This parameter is needed to predict the energy delivered to the bit with each hammer cycle.

$$\text{P} = E_P \cdot f$$

  where P is the hammer power and f is the hammer cycle frequency.

- Rotational Energy, E_R [ft-lb] – This is the energy required to rotate the bit and depends upon the torque necessary to rotate the bit to the next position. The torque was determined by measuring the hydraulic pressure at the input to the motor on the test rig, and the torque was subsequently determined from the manufacturer's performance specifications for the positive displacement motors on the drill rig.

$$\text{E}_\text{R} = 2\pi \, \text{T}$$

- Rotational Power, P_R [W] – This torque, along with the rotational speed, is used to determine the rotational energy requirements for given bit designs.

$$\text{P}_\text{R} = N \cdot \text{T}$$

- Total Energy, E_T [ft-lb] – The total energy is the sum of the percussive energy delivered from the piston and the rotational energy determined from the measurements of the reactive torque. The total energy input to the bit per revolution is computed as follows:

$$E_T = E_P \cdot bpr + E_R = E_P\left(\frac{f}{N}\right) + 2\pi T$$

  where

  E_P is the energy per hammer piston impact (ft-lb),
  f is the hammer frequency (Hz),
  N is the rotary speed (rpm),
  f/N is the number of impacts per revolution, and
  T is the average torque per revolution (ft-lb).

- Specific Energy, E_s [ft-lb] – The specific energy is a measure of the energy required to remove a given volume of rock, typically in one bit revolution. It is defined as follows:

$$E_s = \frac{E_T}{V}$$

  where V is the volume of rock removed per revolution (in^3) and is calculated using

$$V = A \cdot \delta$$

  where A is the bit area (in^2) and δ is the depth of cut per revolution (in/rev).

- Theoretical Rate of Penetration, ROP_t [ft/hr]– A theoretical ROP can be derived by neglecting the work due to torque and solving the specific energy equation for ROP:

$$ROP_t = \frac{E_P\left(\frac{f}{N}\right)}{\frac{AE_s}{N}} = \frac{E_P \cdot f}{AE_s} = \frac{T_R P}{AE_s} = \frac{4T_R P}{\pi d^2 E_s}$$

  where d is the bit diameter (in.).

Assuming the specific energy to be equal to the compressive strength of the rock, and by using a 100% efficiency for the transmitted energy to the bit, this expression may be used to predict a theoretical upper limit on the bit response and evaluate the effectiveness of a given bit and hammer design.

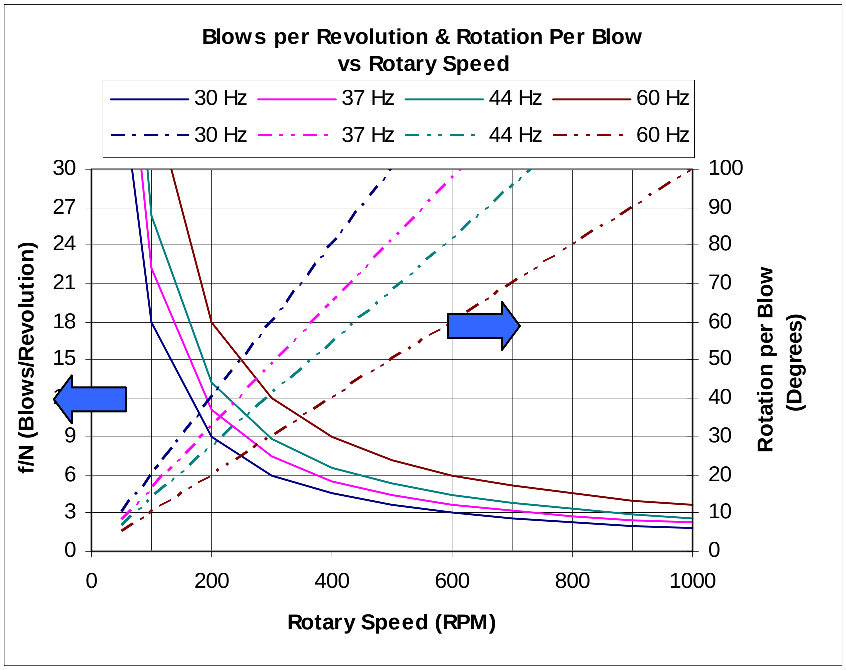


Figure J-4. Bit impacts per revolution.

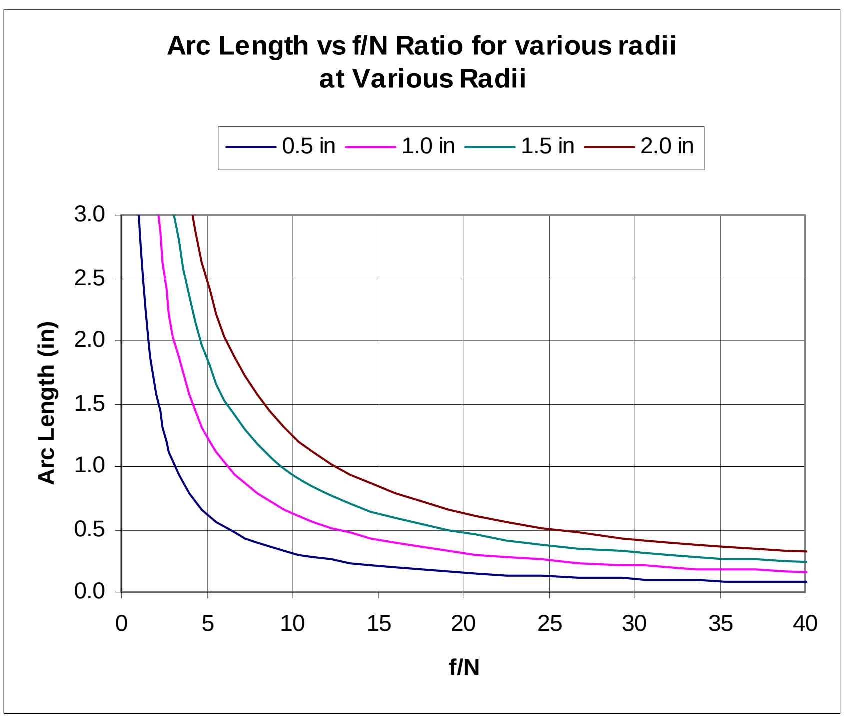


Figure J-5. Button advance along an arc.

Appendix K. Example Web site Development

K.1 Example Web Site Development

K.1.1 Concept

The concept behind the NIOSH web site is to provide a centralized resource for mine rescue drilling information. The web site will focus primarily on the MRDS being developed. It will also serve to present real-time information on mine rescue operations and available equipment. Users will be able to post rescue events and search for information related to mine rescue operations. A graphical representation of a possible structure is shown in Figure K-1. Navigating outward from the central hub will facilitate communication about various aspects of the MRDS, including overall system information, equipment status, qualified contractors and resources on mines within a given area, and a password-protected event-monitoring hub for use during an actual rescue event.

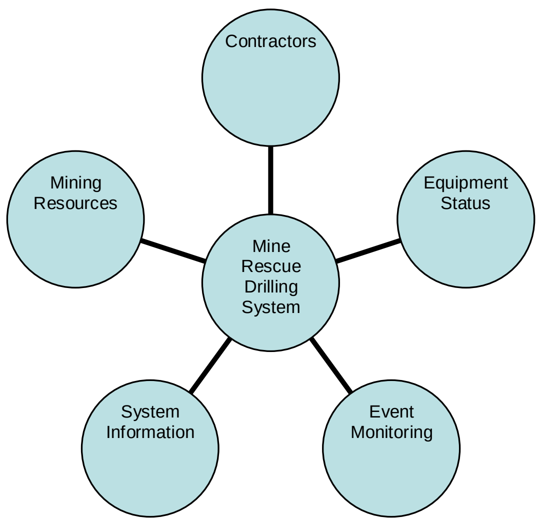


Figure K-1. Graphical structure of proposed MRDS web site.

K.1.2 Example Layout

An example web site was created to illustrate the utility of such a web site for an MRDS. The web site is laid out in a three-column format (see Figure K-2). The left column provides links to important information on the web site, including MRDS information, equipment status, links to qualified contractors, and event monitoring. The center column presents the primary content for the page. The right column contains links to external mining resources.

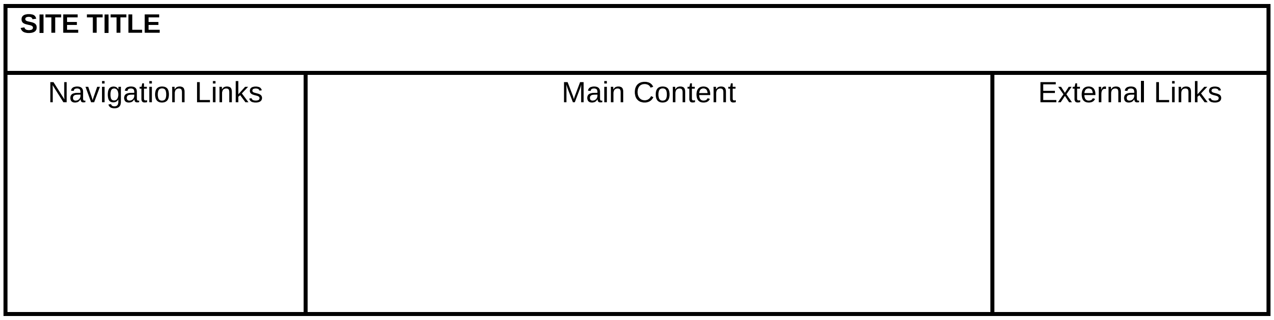


Figure K-2. NIOSH web site layout.

The main content will include information relevant to the mine rescue operations. The following figures show the content for the main pages on the MRDS web site. Figure K-3 shows the basic layout for the MRDS, including the requisite surface equipment and the BHA.

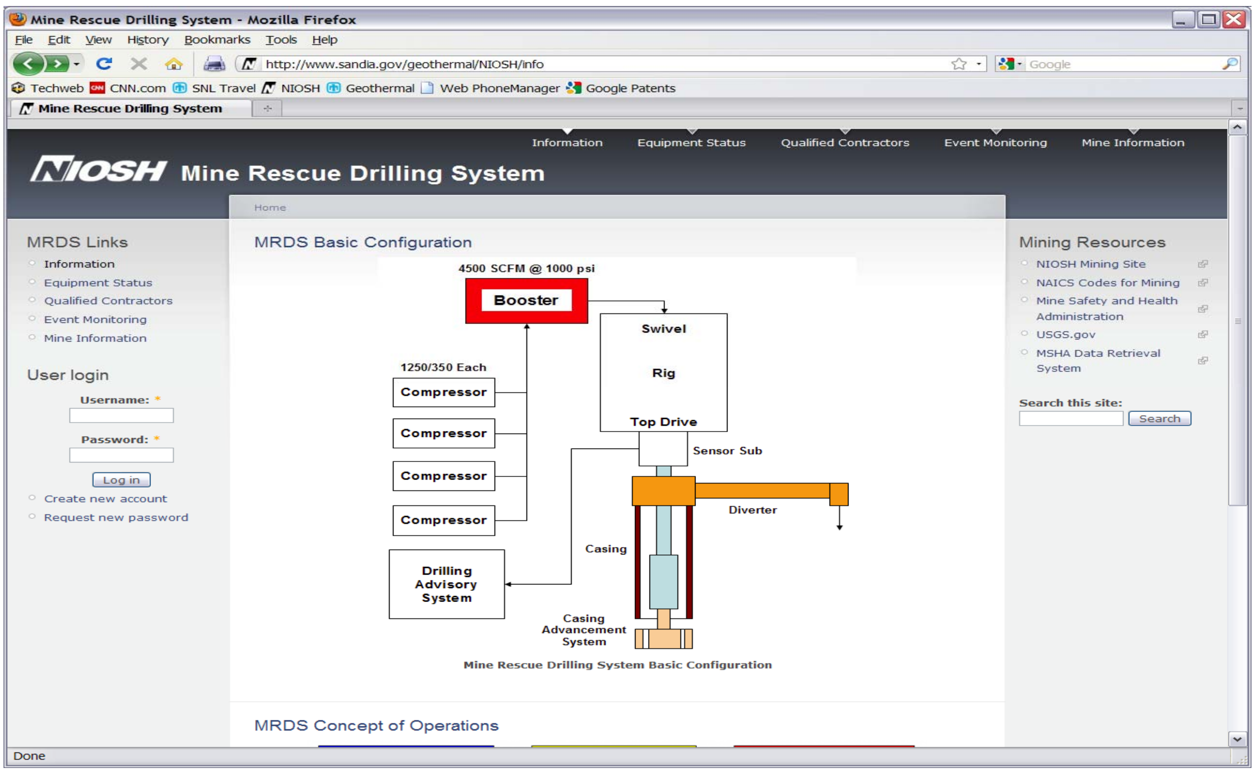


Figure K-3. MRDS basic configuration.

Figure K-4 displays the typical event-monitoring page. The page gives the mine location and event description along with a rescue status. The contractor deployed to the rescue site is also listed, along with the MRDS rescue equipment being used in the operation. This page is intended to be monitored by authorized users during rescue events.

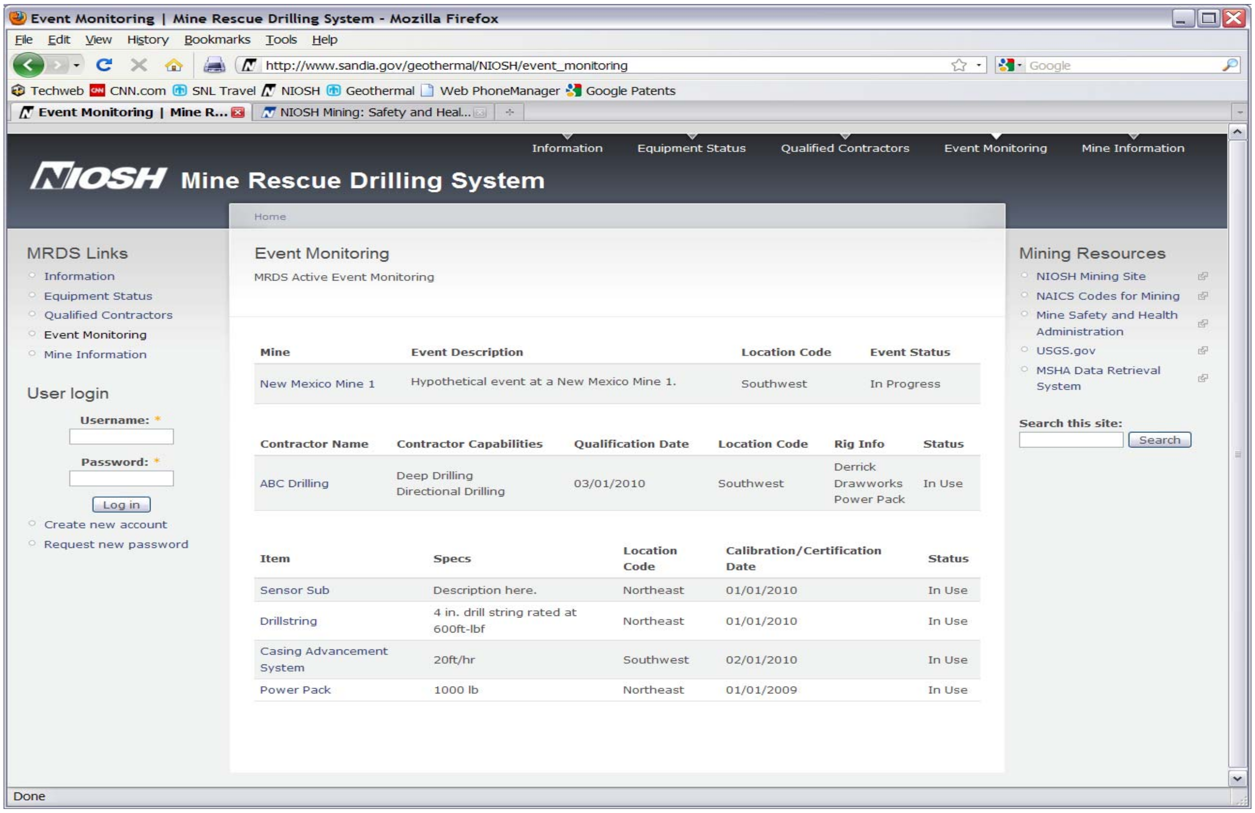


Figure K-4. MRDS event monitoring.

Figure K-5 shows the qualified contractors page. The page gives information about drilling contractors in the region who are qualified to use the rescue equipment. The page lists the contractors and their capabilities. The qualification date indicates a scheduled date for ensuring the contractor is aware of the latest drilling system and its use.

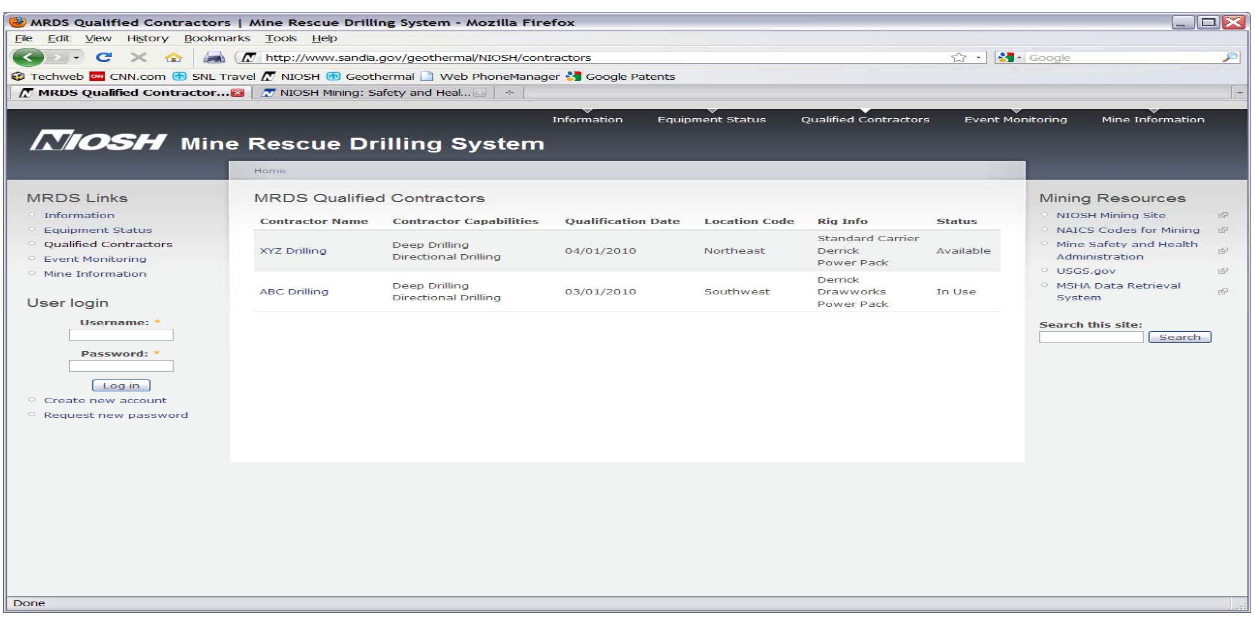
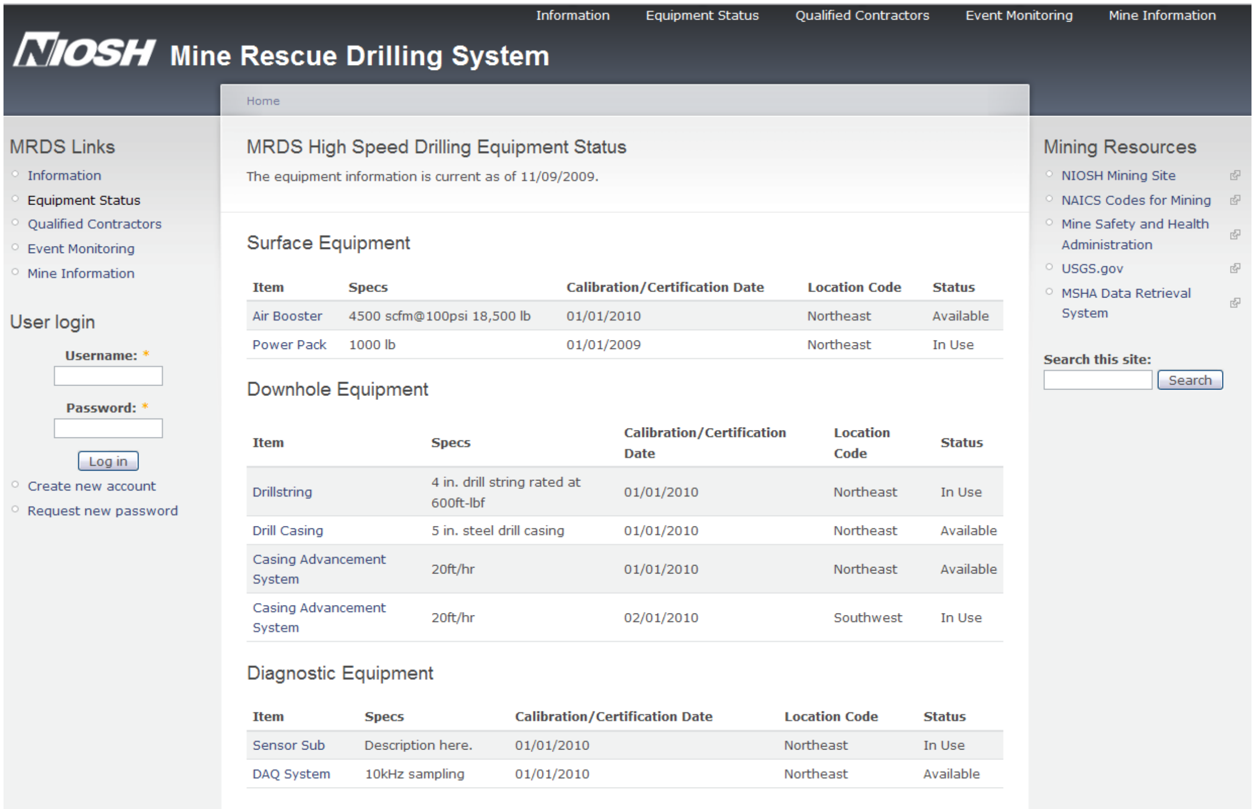


Figure K-5. MRDS qualified contractors.

Figure K-6 shows the equipment status page. This page lists the inventory of MRDS equipment that has been deployed or is in storage. It allows real-time tracking of available equipment and its status. The intent of this page is to make it easy to trace and locate equipment when it is needed.


Information Equipment Status Qualified Contractors Event Monitoring Mine Information

NIOSH Mine Rescue Drilling System

Home

MRDS Links
- Information
- Equipment Status
- Qualified Contractors
- Event Monitoring
- Mine Information

User login

Username: *

Password: *

Log in

- Create new account
- Request new password

MRDS High Speed Drilling Equipment Status

The equipment information is current as of 11/09/2009.

Surface Equipment

Item	Specs	Calibration/Certification Date	Location Code	Status
Air Booster	4500 scfm@100psi 18,500 lb	01/01/2010	Northeast	Available
Power Pack	1000 lb	01/01/2009	Northeast	In Use

Downhole Equipment

Item	Specs	Calibration/Certification Date	Location Code	Status
Drillstring	4 in. drill string rated at 600ft-lbf	01/01/2010	Northeast	In Use
Drill Casing	5 in. steel drill casing	01/01/2010	Northeast	Available
Casing Advancement System	20ft/hr	01/01/2010	Northeast	Available
Casing Advancement System	20ft/hr	02/01/2010	Southwest	In Use

Diagnostic Equipment

Item	Specs	Calibration/Certification Date	Location Code	Status
Sensor Sub	Description here.	01/01/2010	Northeast	In Use
DAQ System	10kHz sampling	01/01/2010	Northeast	Available

Mining Resources
- NIOSH Mining Site
- NAICS Codes for Mining
- Mine Safety and Health Administration
- USGS.gov
- MSHA Data Retrieval System

Search this site:

Search

Figure K-6. MRDS equipment status.

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10	MS 1033	David W. Raymond	06916
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1	MS 1033	Steven D. Knudsen	06916
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1	MS 1153	David R. Gardner	05444
2	MS 0899	RIM-Reports Management	09532

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