Forty Year History of Testing at NIOSH's Mine Roof Simulator. What have we learned?

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ABSTRACT

The National Institute for Occupational Safety and Health's (NIOSH) Mine Roof Simulator (MRS) at the Pittsburgh Mining Research Division was commissioned for operation in 1981. The MRS was originally designed for longwall shield research and was the only hydraulic press in the world with the capability to apply biaxial loads to these large structures. The results of this forty-year research program have contributed to improved performance and increased knowledge of longwall shields, mobile roof supports and hydraulic cylinders in the mining industry. Also, considerable research and development have been conducted to develop standing support technologies for the mining industry. The Support Technology Optimization Program (STOP) was developed to evaluate how these various technologies can impact and improve both ground control conditions and mine safety. Additional MRS research has included the performance of ventilation stopping walls including the development of a new testing protocol to evaluate the transverse loading capabilities under arching load conditions and evaluating the performance characteristics of welded wire screen as used in underground mine roof surface control. The NIOSH Mine Roof Simulator has been a reliable and valuable tool for the past forty years for the evaluation of safety structures used in mining, and this research has contributed significantly to the advancement toward safer mines. This paper will summarize those research results and provide a glimpse of planned future activities.

INTRODUCTION

Unplanned roof falls have been a major obstacle to coal mine safety and production ever since coal mining began. Improving the design, selection, and operation of roof support systems can ultimately reduce roof fall failures while also improving coal production. Initially in the 1960s, some early U.S. longwall faces were equipped with chock supports but had to be abandoned because of their inability to resist horizontal displacements and the resulting moment loading caused by the strata dynamics during the caving process. In the 1970s, shield supports were then introduced and were better able to resist these mine conditions, improving both ground conditions and longwall production. The success of the shield support promoted the increased application of the longwall mining method in highly faulted and massive strata conditions **[1]**. This new technology led the U.S. Bureau of Mines (now NIOSH) and the U.S. Department of Energy to design a machine specifically for testing mine roof support systems. The Mine Roof Simulator (MRS), located at NIOSH's Pittsburgh Mining Research Laboratory, is one of the premier facilities in the world for testing mine roof supports. Forty years of research at the MRS has produced important contributions to the advancement of ground control and safety in coal mines around the world.

As part of NIOSH's mission to reduce hazards to the miner through development of improved ground control technologies, four main areas of research that were conducted at the MRS will be covered in this paper: (1) powered supports, (2) standing supports, (3) ventilation stoppings, and (4) roof surface control. Research to investigate both the mechanical and hydraulic performance of longwall shields and mobile roof supports has been conducted. This research, including laboratory testing, computer modeling, and field measurements, resulted in improved caving shield and lemniscate designs for shields and an operator safety system for mobile roof supports. A further contribution to mining safety developed through research at the MRS was the Support Technology Optimization Program (STOP) **[2]**. This software program was based on the results of thousands of tests on secondary standing supports and enables the user to apply engineering principles to the selection and placement of these supports in the mine. Additional MRS research investigated the performance of ventilation stoppings to resist lateral (transverse) forces on the face of the structure to control pressure differentials. Although stoppings are primarily constructed to direct the airflow in the mine, their contribution to ground control and material handling issues were addressed in the research. Finally, laboratory tests on the load-displacement characteristics of welded-wire roof screen were conducted on isolated sections of screen using various-sized pull point contact areas to simulate the effects of various sizes of roof failures. All these benefits to the mining industry are the result of research conducted using the NIOSH Mine Roof Simulator.

MINE ROOF SIMULATOR: DESCRIPTION AND CAPABILITIES

The MRS is a computer-controlled electro-mechanical hydraulic press designed to provide a realistic simulation of the closure of a mine roof on roof supports over either a rapid or slow change in roof characteristics. Roof supports for longwall mining represented a key element for the successful application of this mining method in the U.S., and the MRS was designed specifically to conduct research on these supports. The MRS was custom built by MTS Systems Corporation to U.S. Bureau of Mines (USBM) specifications. It was designed specifically for longwall shield testing and is the only active load frame in the United States that can accommodate full-size shields. However, its size and unique capabilities provide a facility for testing a wide variety of large-scale structures, including various forms of standing roof support structures and mine ventilation stoppings.

The MRS diagram of the machine in Figure 1 shows several distinctive characteristics. The upper platen is movable to allow variation in the vertical test space from zero to sixteen feet. The upper platen is clamped to the smooth vertical columns at the desired height, with adjustable lateral struts used to react to the horizontal and lateral leads. The lower platen applies loads, as programmed, to the test specimen. The platens are 20 feet square. The lower platen can apply 3,000 kips vertically and 1,600 kips horizontally, with a usable displacement range of 24 inches vertically and 16 inches horizontally. Four vertical actuators, four horizontal actuators, and four lateral actuators at the lower platen comers are used to apply and react to the force. Hydrostatic slip bearings permit simultaneous load application and travel. Horizontal and vertical travel are programmable simultaneously. Full loads can be applied anywhere over 70% of the platen area. Each individual vertical actuator can apply about 2,800 kips.

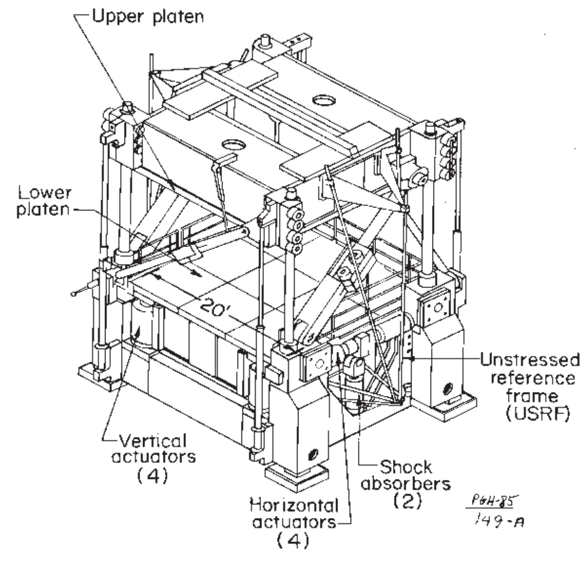

Figure 1 - Diagram of the Mine Roof Simulator

Six degrees-of-freedom control of the lower platen are provided by the unstressed reference frame which provides feedback on platen displacements and rotations to the closed-loop control system. This tripod super structure on two sides of the simulator is used for measuring the relative motion of the two platens. Its purpose is to allow control of the center position of the lower platen without having to compensate for deflection of the frame structure. Pitch, roll, and yaw of the lower platen are controlled to keep the lower and upper platens parallel and aligned during load application. The velocity of the lower platen can be controlled from 0.05 to 5.0 inches per minute and load application rates of up to 50 tons per second.

Additional support instrumentation includes load cells, string pots, strain gauges, pressure transducers, extensometers, and linear potentiometers. Thirty-two conditioners are provided for real-time monitoring of data and storage for future analysis by the MRS computer. A load cell is a transducer used to create an electrical signal whose magnitude is directly proportional to the force being measured. Pressure transducers are used to measure hydraulic pressures; sting pots, extensometers and potentiometers are used to measure vertical and horizontal displacement, and strain gauges are used to measure material strain in areas where maximum stresses are estimated to occur.

For example, strain gauges monitor deformation and are essential to an analysis of the structural behavior of shield roof support systems. MRS testing has shown cases where material failure was experienced prior to hydraulic yield, indicating that protection from yield valves alone is insufficient to evaluate support performance. Furthermore, there is not always a direct relationship between leg pressure and strain; certain elements of a support will show increased strain, while leg pressure remains constant as loads are applied.

LONGWALL SHIELD RESEARCH

A longwall shield (*Figure 2*) is a relatively simple mechanism with few components, but the behavior of the structure under biaxial loading is quite complex. With the ability of the MRS to apply biaxial loads and measure this behavior, a new protocol for testing shield supports was established. The biaxial capability of the MRS can produce loading profiles that replicate the actual ground movements on a longwall face. The advantage is that the load is applied to the shield structure by the relative motion of the MRS platens rather than the point load being generated by the hydraulic cylinders of the shield in a static frame. The biaxial capability of the MRS provides for direct control and measurement of the critical horizontal forces acting on the shield.

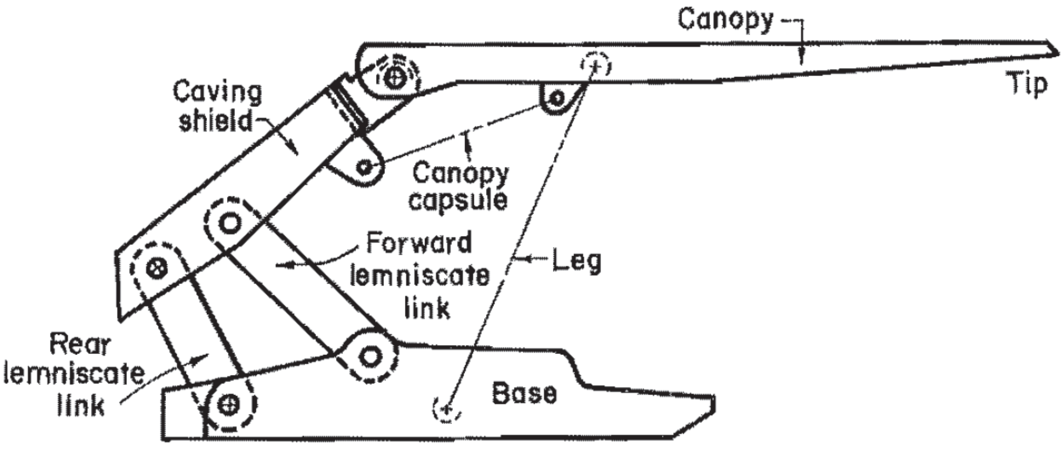

Figure 2 - Components of longwall shield. [2]

Early testing conducted in cooperation with shield manufacturers utilized the biaxial capability of the MRS to direct the loading path through the caving shield and lemniscate linkage of the support. These tests revealed the stress concentrations that could occur from horizontal face-to-waste displacements and waste-to-face loads that resulted in more robust designs of the caving shield and lemniscate components. Later research led to the development of shield testing protocol utilizing the unique active loading capabilities of the MRS to provide enhancement over conventional static loading frame. Severe bending and torsion of the canopy and bases and/or high horizontal loads that cause extreme stress in the caving shield and lemniscate links were identified. Cyclic fatigue tests were also conducted on several different shields that showed the severe wear that occurs in the pin bores of the rear linkage. These test protocols identified conditions that could cause difficulties underground ranging from operational issues to structural component failures. Additional research performed also determined the stiffness characteristics of a shield and its sensitively to setting pressure, boundary conditions, and operational height and a methodology to access resultant loading on active longwall shields during cycle loading operation in the mine. Comparable studies have been conducted on mobile roof supports to evaluate their performance for retreat mining applications. Details of the MRS shield research results have been previously published **[1, 3, 4, 5, 6, 7]**.

The knowledge gained by testing longwall shields in the MRS laboratory and a review of field data has identified two areas of safety and performance issues for powered supports. These are the shield structure and the hydraulic systems. Structural failures due to fatigue or over-stressing do still occur. For bases with high stiffness, the socket welds can shear or the toes can be permanently deformed. The cracking of welds along the side plates are also caused by bending. Permanent deformation of the canopy from bending is a common occurrence, but destruction or complete failure is less likely. The rear linkage and caving shield experience torsion and bending which can cause cracking, and the pin connection areas are subject to wear from high stresses. The pin bores can become elongated and develop stress concentrations that lead to cracks. The knowledge and experience gained through testing powered supports at the MRS have been compiled to create guidelines for the selection of powered roof supports for longwall mining **[8, 9]**.

STANDING SUPPORT RESEARCH

Innovative support developments have traditionally been a major component of the facility utilization since the early 1990s, which has significantly contributed to the development of a host of new roof support products that have changed the landscape of standing support practices. Considerable research and development have been conducted by support manufacturers to develop standing support technologies for the mining industry. Researchers from NIOSH, with the cooperation of various support manufacturers, have developed a testing protocol that evaluates performance characteristics of these standing support systems. MRS testing protocols have been developed to utilize the capabilities of the MRS to evaluate the strength, stiffness, and stability of standing support products **[10]**. The baseline performance of the support is determined from a vertical-only loading cycle. The impact of horizontal loading can be tested using a biaxial load profile, typically with a 3-to-1 or 2-to-1 vertical to horizontal displacement ratio. The limits of stability can be determined by testing the support to failure by varying the support configurations that include aspect ratio and asymmetric boundary (contact) conditions. Other factors affecting performance such as a setting load or load rate sensitivity can also be evaluated.

MRS standing support testing identifies distinct differences in performance characteristics that define the loading behavior of various standing roof support systems **[11, 12, 13]**. An assessment of these performance characteristics shows that a range of alternatives exist among the various roof support systems that are now available. When determining the evaluation criteria of standing supports, several parameters (stiffness, yield and peak load capacity, roof contact area and residual load characteristics) need to be examined when selecting a standing support system. For example, a greater peak load capacity does not necessarily translate to a support capable of being able to withstand a larger convergence. Even with a high peak load capacity, the support might not be the most effective standing support system for a particular mine. If a support reaches its peak load capacity before the equilibrium ground conditions are met and is unable to sustain the required capacity to achieve equilibrium, failure of the rock mass (mine roof) results.

The ground reaction curve (GRC) can be used to assist in determining the compatibility and design requirements for a support system. It is important to understand the significance of the ground reaction relative to the support design requirements. The ultimate objective is to match the support behavior to the ground response and create equilibrium (stability) of the rock mass. This equilibrium is accomplished when the support loading intersects the ground reaction curve (Figure 3). Essentially, the ground reaction concept implies that the convergence in the mine entry is controlled by the magnitude of the support resistance. However, typically used as a passive support, the standing support develops its loading through convergence. As such, the support needs to maintain its load capacity through the associated deformation of the ground and resulting entry convergence until the equilibrium condition is reached. This requirement causes factors such as the support stiffness, peak capacity, yielding characteristics, and stability to be fundamental to proper support design and application. NIOSH contributes to providing this understanding through full-scale performance testing of support products in the Mine Roof Simulator. Details of the ground reaction curve results have been previously published **[14, 15, 16]**.

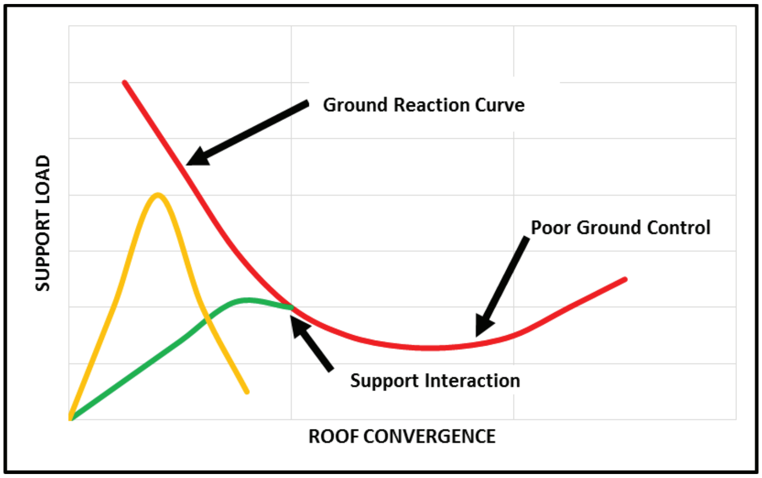

Figure 3 - Illustration of Ground Reaction Curve.

A large database of support performance has been developed through the stakeholder testing in the MRS. To facilitate transfer of this information to the mining community and to provide the basis for selecting supports based on the performance characteristics of the support, a design program called the Support Technology Optimization Program (STOP) was developed **[16, 17, 18, 19]**. This was the first-ever software of its kind for standing roof support design and was widely accepted by the mine operators, support manufacturers, and regulators. The program provided a full description of the performance characteristic for each support and provided a basis for design for the following conditions: 1) supporting weight of a detached roof block, 2) designing around a ground reaction curve, and 3) equivalent support design whereby an alternative support system can be designed to provide equivalent performance to an existing support system that has proven to provide acceptable support.

VENTILATION STOPPINGS RESEARCH

Stoppings are a key component of underground mine ventilation systems. Permanent stoppings are often constructed from some form of concrete block, typically dry-stacked to form a wall, equal in thickness to the narrow or wide dimension of the block and bridging between the mine roof and floor and pillar ribs. Stoppings are required to resist transverse loads on the face of the structure to control pressure differentials created by ventilating air. A laboratory testing protocol to simulate rigid arching (transverse force) of stopping walls by biaxial loading in the MRS (Figure 4) was developed and verified through field measurements of stopping failures. **[20]**.

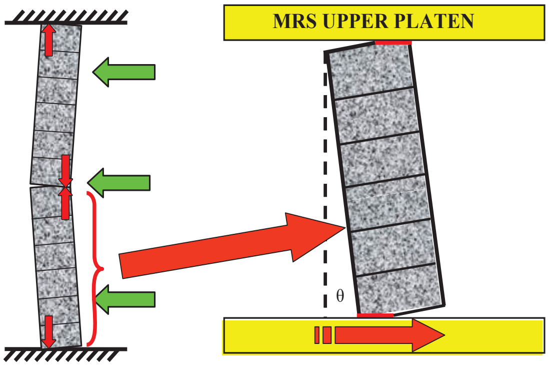

Figure 4 - MRS lateral load testing protocol.

The results confirm the theoretical analysis that both the compressive strength of the construction material and the thickness of the wall have a significant impact on the transverse load capacity of a stopping. Therefore, since most blocks are dimensionally anisotropic, constructing the wall with the wide side of the block in contact with the adjacent block layer during wall construction can significantly increase the transverse load capacity of the stopping. For example, increasing the wall thickness from 6.0 to 7.5 in increased the transverse load capacity of a 7.5-ft-high wall by a factor of 2.6. Conversely, increasing the height of the stopping will reduce the transverse load capacity in an even more dramatic fashion. The transverse load capacity dropped by nearly an order of magnitude when the 6-in-thick wall doubled in height from 5 to 10 ft. Details of the transverse load capacity of mine ventilation stopping results have been previously published **[21, 22, 23]**.

ROOF SCREEN SURFACE CONTROL

Large numbers of ground-fall injuries are not often caused by major roof collapses, but from falls of smaller rocks from the immediate roof. Roof screen can significantly reduce the number of these injuries and has been widely used in underground coal mines for surface control. Because of the potential of reducing ground-fall injuries, NIOSH evaluated the performance characteristics of welded-wire screen as used in underground coal mines by conducting a laboratory testing program using NIOSH's Mine Roof Simulator.

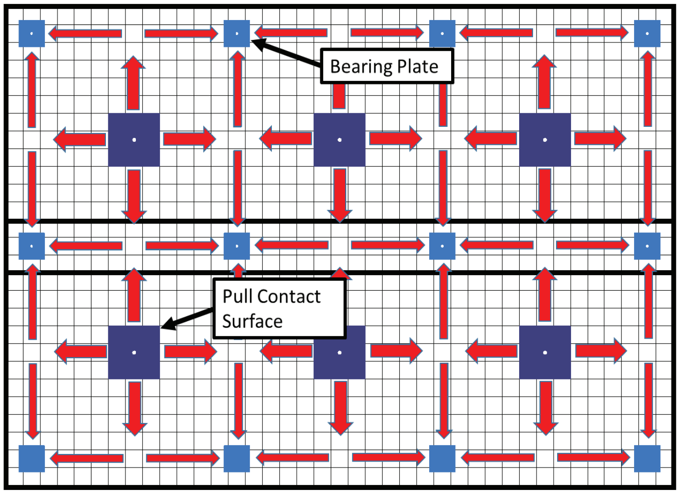

Figure 5 - Schematic of screen test configuration with square bolting pattern with respect to the screen. The arrows indicate the load transfer directions from the pull plates to the bearing plates.

Research was conducted to study the effects of varying the load contact area and position of the load-pull location to simulate a large roof fall. A schematic of the screen test configurations with the bearing plate bolting pattern and an example of the pull contact area is shown in Figure 5. This bolt pattern is consistent with the typical installation currently used in underground coal mines. With this test configuration, the screen loading is transferred from the load area through the corresponding screen wires crossing the loading contact area, then typically to the perpendicular wires that directly connect to the bearing plates **[24]**. Figure 6 shows the various configurations of the test layouts and pull locations for a series of tests. The loading is measured with a load cell(s) at each of the pull locations.

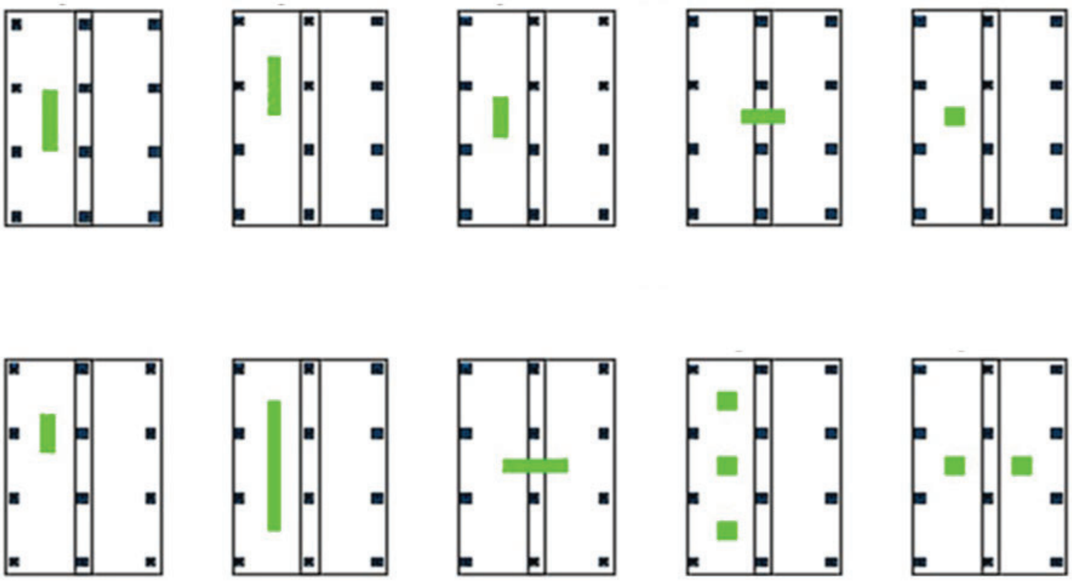

Figure 6 - Example of tests configurations conducted in this study (pull locations shown in green).

This research showed how the effects of load location, contact size, and single contact versus multiple contacts of the load with respect to the bearing plate bolt pattern can influence the screen response and performance. When the applied load is directed between the bolted pattern, the load capacity and stiffness of the screen is decreased. There is also an increase in the number of wire breaks associated with the location change of the load with respect to the bolt bearing plates. A larger contact area increases the screen load capacity when the applied load is contained within the center of the bearing plate bolting pattern. However, if the load contact geometry extends beyond the bolting pattern, the load capacity can be decreased. It was observed that the multiple smaller contacts resulted in a larger yield and peak load capacity. This is probably caused by the large load contact area applying load between the bolting pattern and decreasing the load capacity of the screen. The exception for this behavior is when the applied load is across overlapped sections of screen. When this occurs, the load capacity of the screen is larger with the single large contact than the multiple smaller contacts. Details of the behavior of full-scale welded-wire screen for mine roof skin results have been previously published **[25, 26, 27, 28]**.

SUMMARY AND FUTURE MRS RESEARCH

The MRS has been an extremely useful and reliable tool for forty years. The foresight and effort to design and construct the Mine Roof Simulator with its unique capabilities for mining research has certainly been worthwhile. The research into shield behavior and performance, secondary roof supports, ventilation structures, and screen roof control has advanced the knowledge of the equipment used to control the ground and to ensure safe travel-ways and proper mine ventilation.

There are still several research areas that would benefit from further study. The MRS has the scale and capacity to conduct large-scale testing of rock mass or coal sections as opposed to smaller scale samples that are used in material testing. Mining research has the burden that material responses beyond the elastic range are common, resulting in damage that translates into post-failure response of the rock mass. Understanding the post-failure residual behavior of rock materials is important to comprehending ground response and support intervention effectiveness. The scale increase would be from inches to feet when considering the structural approach. The goal of this research would be to gain insight into determining the load-deformation response of the mining scale structure, i.e., coal pillar or a section of rock mass, and how this may differ than using laboratory-scale material properties in the engineering assessment of these structures that form the basis for current design criteria.

While various forms of instrumentation have been developed and utilized, the calibration and interpretation of the instruments continues to be less than ideal. Although various instruments are designed differently and work to measure the stress in different ways, the fundamental goal of calibration is to test the full system, meaning the instrument and host material. Direct loading of the instrument is insufficient since the act of installing the instrumentation and/or the interaction of the instrument with the surrounding material can change the local stress that impacts the stress instrument response and reading. The MRS provides an opportunity to provide controlled loading at mine-scale levels to verify calibration of such instrumentation.

Standing supports have been used in coal mines for decades to enhance roof support capability. Standing supports are sometimes used to resist lateral deformation of spalled ribs. Standing support systems can be used to stabilize fracture rib brows, restrain detached rib slabs, or in combination with mesh, providing additional confinement to hold spalling material in place. The objective of this research program would be to reduce the number of coal rib-fall accidents in coal mines by developing an engineering-based design methodology that assesses the performance characteristics of various standing support systems used to contain rib sloughing. This research will provide information regarding the axial and lateral loading capacity of different types of standing supports under different prop-end conditions. From these observations, mining operations can improve their technique for rib reinforcement.

The research that has been accomplished using the Mine Roof Simulator has helped to make mining safer. Improvements to shield support design has made longwall mining and standing secondary supports successful, which has reduced injuries to miners. Also, research into the factors affecting the performance of ventilation stoppings will optimize material selection and reduce material handling injuries to miners. Finally, the type of information obtained from these full-scale roof screen tests can be used to aid in developing design criteria and to assist mine operators in the selection and layout of roof screen in underground mines.

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DISCLAIMER

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