Horizon Sensing (Proposal #51)
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Disclaimer

Abstract

With the aid of a DOE grant (No. DE-FC26-01NT41050), Stolar Research Corporation (Stolar) developed the Horizon Sensor (HS) to distinguish between the different layers of a coal seam. Mounted on mining machine cutter drums, HS units can detect or sense the horizon between the coal seam and the roof and floor rock, providing the opportunity to accurately mine the section of the seam most desired. HS also enables accurate cutting of minimum height if that is the operator's objective. Often when cutting is done out-of-seam, the head-positioning function facilitates a fixed mining height to minimize dilution. With this technology, miners can still be at a remote location, yet cut only the clean coal, resulting in a much more efficient overall process.

The objectives of this project were to demonstrate the feasibility of horizon sensing on mining machines and demonstrate that Horizon Sensing can allow coal to be cut cleaner and more efficiently. Stolar's primary goal was to develop the Horizon Sensor (HS) into an *enabling* technology for full or partial automation or "agile mining". This technical innovation (R&D 100 Award Winner) is quickly demonstrating improvements in productivity and miner safety at several prominent coal mines in the United States. In addition, the HS system can enable the cutting of cleaner coal. Stolar has driven the HS program on the philosophy that cutting cleaner coal means burning cleaner coal.

The sensor, located inches from the cutting bits, is based upon the physics principles of a Resonant Microstrip Patch Antenna (RMPA). When it is in proximity of the rock-coal interface, the RMPA impedance varies depending on the thickness of uncut coal. The impedance is measured by the computer-controlled electronics and then sent by radio waves to the mining machine. The worker at the machine can read the data via a Graphical User Interface, displaying a color-coded image of the coal being cut, and direct the machine appropriately.

The Horizon Sensor program began development in 1998 and experienced three major design phases. The final version, termed HS-3, was commissioned in 2000 with the assistance of the DOE-Mining Industry of the Future program, commercialized in 2002, and has been used 14 times in 12 different mines within the United States. The Horizon Sensor has applications in both underground and surface mining operations. This technology is primarily used in the coal industry, but is also used to mine trona and potash. All horizon sensor components have Mine Safety and Health Administration (MSHA) (United States) and IEC (International) certification.

Horizon Sensing saves energy by maximizing cutting efficiency, cutting only desired material. This desired material is cleaner fuel, therefore reducing pollutants to the atmosphere when burned and burning more efficiently. Extracting only desired material increases productivity by reducing or eliminating the cleaning step after extraction. Additionally, this technology allows for deeper mining, resulting in more material gained from one location. The remote sensing tool allows workers to operate the machinery away from the hazards of cutting coal, including noise, breathing dust and gases, and coal and rock splintering and outbursts.

The HS program has primarily revolved around the development of the technology. However, the end goal of the program has always been the commercialization of the technology and only within the last 2 years of the program has this goal been realized. Real-time horizon sensing on mining machines is becoming an industry tool. Detailed monitoring of system function, user experience, and mining benefits is ongoing.

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Abbreviations and Acronyms

AC	alternating current
AHr	ampere-hour
BDC	bottom dead center
BM	bore miner
CAD	computer-aided design
CBI	Cutter Boom Inclinometer
CCRB	Clean Coal Review Board
CCT	Clean Coal Technology
CFS/D	Coherent Frequency Synthesizer Detection
CM	continuous miner
DB	decibels
DC	direct current
DOE	Department of Energy
FEA	finite element analysis
FFT	fast Fourier transform
FNR	Forward Nominal Response
GMA	GUI Modem Aerial
GPIB	GUI Power Input Board
GUI	Graphical User Interface
HBU	Horizon Battery Unit
HGR	Horizon Graphics Remote
HGU	Horizon Graphics Unit
HHC	hand-held chassis
HP	head positioning
HPU	Horizon Power Unit
HS	Horizon Sensor
HS-BM	Horizon Sensor bore miner
HS-CM	Horizon Sensor continuous miner
HS-HW	Horizon Sensor highwall
HS-LW	Horizon Sensor longwall
HS-RMPA	Horizon Sensor with Resonant Microstrip Patch Antenna
HSU	Horizon Sensor Unit
I.S.	Intrinsically Safe
LCD	liquid crystal display
LCM	Linear Cutting Machine
LED	light emitting diode
LW	longwall
mA	milliampere
MCC	Monterey Coal Company
MSHA	Mine Safety and Health Administration
OCDO	Ohio Coal Development Office
OD	outside diameter
OEM	Original Equipment Manufacturer

Abbreviations and Acronyms (Concluded)

PBP	portable battery pack
PCA	pulse count algorithm
PCB	printed circuit board
PGH	portable graphics head
PSD	power spectral density
PSH	portable sensor head
RAMP	Revised Approval Modification Program
RC	regulation and control
RCP	recording control parameters
RF	radio frequency
RFI	not defined (section 3.2.2)
RMPA	Resonant Microstrip Patch Antenna
RMS	root mean square
ROM	run-of-mine
RPM	revolutions per minute
SFR	stepped-frequency radar
SHM	Superior Highwall Mining
SPD	spectral density
TDC	top dead center
TOVCC	The Ohio Valley Coal Company
VAC	volts alternating current
VDC	volts direct current
VNA	vector network analyzer
WVU	West Virginia University
X/P	explosion proof

1. HS Program Introduction

When cutting coal, the operator cannot always see the cutter drum and bits impacting the coal seam or surrounding strata (either on a longwall shearer or continuous miner). Thus, the mining industry will greatly benefit from a technology that provides real-time detection of the seam horizon during mining operations. At a recent CEO workshop sponsored by the US National Mining Association, horizon sensing was identified as one of the top industry needs or requirements to improve productivity, safety, and coal quality, especially as future mining will be in deeper and possibly thinner seams that have a greater degree of anomalies.

Stolar Horizon, Inc. (Stolar) has spent several years developing the Horizon Sensor (HS) as an *enabling* technology for two specific purposes. This technical innovation (R&D 100 Award Winner) is a critical enabling technology for full or partial automation or “agile mining”. Agile mining leads to improvements in productivity and miner safety. In addition, the HS system can enable the cutting of cleaner coal. Stolar has driven the HS program on the philosophy that cutting cleaner coal means burning cleaner coal.

The HS program has primarily revolved around the development of the technology. However, the end goal of the program has always been the commercialization of the technology, and only within the last 2 years of the program has this goal been realized.

1.1 Cleaner Mining

America’s energy strategy is to rely on its vast reserve of coal. To minimize and reduce the adverse environmental impacts of burning coal, America is developing Clean Coal Technologies (CCT). While the focus of CCT research has traditionally been the process and combustion phases of the coal generation value chain, there is still considerable opportunity to improve environmental performance by producing cleaner coals in the “upstream” production. Cleaner coals, which contain fewer pollutants, such as sulfur, mercury, etc., produce power more efficiently. There is less pollution per kWh. CCT also includes exploration and mining technologies since these technologies can improve coal quality and reduce coal production costs.

There is a critical need for advancements in mine sensor technology designed to identify and extract coal with low sulfur and ash content, resulting in the mining of cleaner burning and more economically efficient coal.

The failure of natural gas supply to keep up with demand has resulted in recent surges in natural gas prices that have had a dramatic dampening impact on the overall U.S. economy. This has caused policy makers to refocus their attention on the need to maintain and increase coal-fired generation. In fact, coal-fired power plants supply about 55 percent of the nation’s electricity. Fortunately, the United States is the “Saudi Arabia” of world coal, with 37 percent of total reserves. While coal is a reliable and plentiful source of energy, its use poses serious environmental issues that must be addressed. Coal seam forming and deposition involves biological and oxygen/reduction chemical processes that concentrate contamination in thin boundary layers next to the seam roof and floor rock. These layers contain much higher percentages of ash, sulfur, and heavy metals. Emissions of sulfur dioxide (SO2) from the combustion of coal are cause for increasing concern because of their potential impacts on human health and contribution to the greenhouse effect. Studies estimate that coal combustion is the source of about 60% of all SO2 emissions from human activities. The introduction of legislation limiting SO2 emissions from coal began in earnest in the 1970s, but has expanded rapidly since the Clean Air Act of the 1990s. Since that point, untold federal and private sector resources have been dedicated toward clean coal research and development.

The vast majority of these resources have focused on post mining technologies, such as coal cleaning to remove sulfur and combustion technologies (such as fluidized combustion) to limit the generation of SO2 and NOX. Not only have these post mining technologies had limited success in dealing with the pending environmental issues, they have greatly increased the cost of coal-fired electricity. High sulfur content coal is expensive to clean, and in addition, ash substantially reduces the power plant heat rate. Both mercury and arsenic are located in thin boundary layers of the coal—a recent EPA concern. Leaving these layers behind in the coal seam would reduce emissions from power plants.

Mining companies begin their search for cleaner coals through exploration. Since future mining will be from deeper and thinner seams, advancements have been made and will continue to be made in exploration technology and techniques. Profiles of deep coal seams reveal multiple levels of coal and sediment strata or layers. And analysis shows that some layers of the coal contain greater levels of pollutants. In fact, some layers are particularly “clean” and contain low levels of ash and rock. The problem is that existing mining techniques do not enable the operator of the coal-cutting machine (who is at a remote location) to distinguish between the different horizons of coal layering. Thus, the “dirtier” coal is cut along with the clean coal producing a less than optimum product. If the operator could see where the band of dirtier coal is and avoid cutting it, a cleaner coal would be produced. Not only would the quality improve, but because less waste is produced, mining efficiency would improve. Credible estimates of coal production in the Pittsburgh seam indicate the cost of mining would be less by as much as $1 per ton – about 7 percent of the variable cost.

The Horizon Sensor is a viable solution to these problems as this technology acts as a guidance system for the operator, detecting the precise location of the various coal and rock horizons. The HS system is mounted in the cutter drum inches away from the bits that cut the coal. This location enables the sensors to take accurate readings of the cutter drum location and the strata in front of the machine. The HS displays for the operator the precise cuts of coal being made. The operator is able to direct the cutting machine into the cleaner coal horizons.

Additionally, the industry needs to advance the geological survey process to confirm that pollutants are layered in coal seams and can thus be isolated. There is limited evidence that perhaps mercury and other heavy metals are restricted to specific layers. If this is the case, and if the layers are at the top or bottom of the coal seams, HS will enable the mining of coal in a manner that leaves mercury behind.

1.2 Agile Mining

In coal mining, engineers have worked hard to identify specific tasks and processes where automation can be applied. However, producing coal from an underground mine has one significant difference when compared with an automated factory above ground. The mine environment is in a constant state of change with respect to physical dimensions and locations of machines. The seam height is always changing, the seam horizon is always changing, and the primary production equipment is always moving. Figure 1.1 illustrates the problem of mining in difficult geologic conditions.

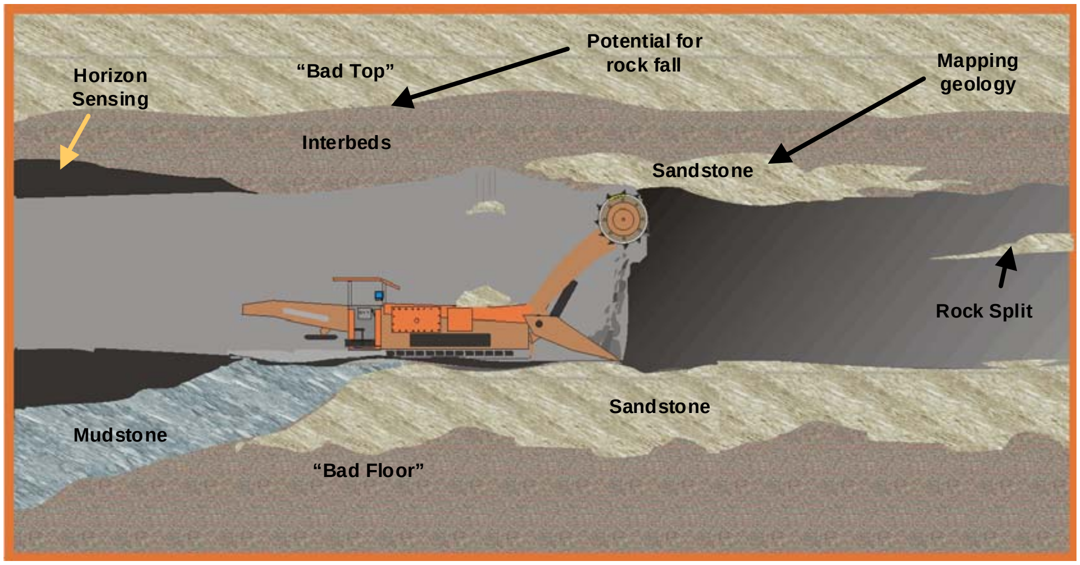


Figure 1.1. Vertical cross section of a coal seam illustrating a continuous mining machine

The variability of geology means that automation in a mine is a greater engineering challenge. While repeatable tasks can be identified and potentially automated, the machines require an extra degree of flexibility. They have to change with the changing mine environment. For example, a longwall shearer may be faced with seam undulation, so each pass or cut needs to be a different height. For true efficiency, the longwall shearer must be able to detect the coal horizon on each pass to set cutting height in real time.

For a shearer application, HS-LW units are installed on each drum (one per drum), with both detectors transmitting real-time measurements to their respective graphical user interfaces (GUIs). The operator can see a display of coal seam thickness to the roof and floor/bottom, as well as drum position or mining height. The display can be modified to accommodate the preference of the operator. In the future, the HS-LW can (or will) be integrated into advance control systems, such as Joy's JNA control. Figure 1.2 depicts the concept of HS units mounted on a shearer.

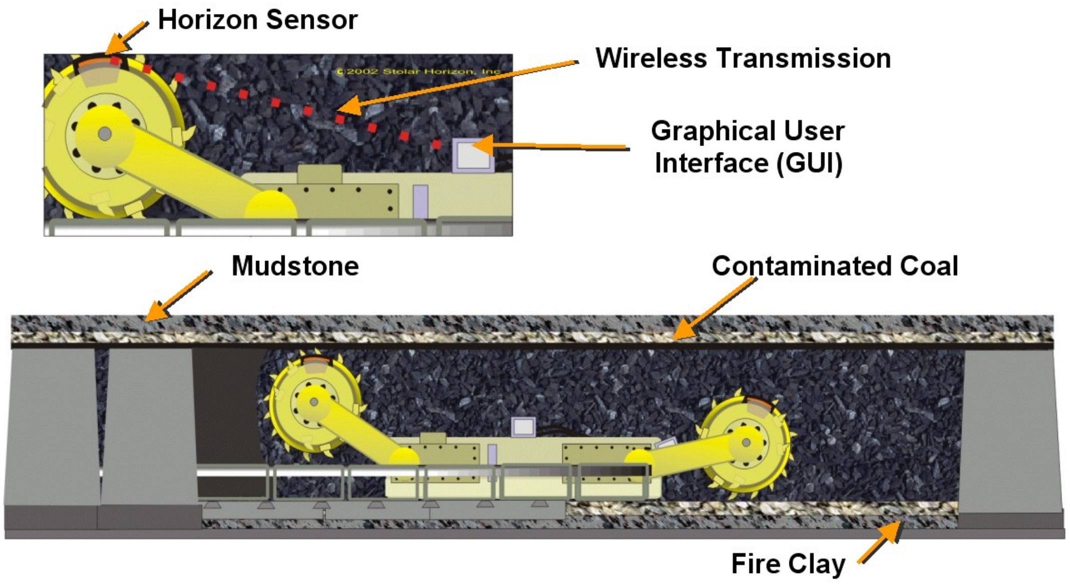


Figure 1.2. HS units mounted on LW shearer drums

This concept of detection and continuous adjustment is a step beyond automation. Machines not only do repeatable tasks, but they behave in an intelligent manner; the machines are flexible or agile. This is the world of “smart mining”.

To achieve “smart mining”, industry experts have identified six core technologies:

- Communications, especially wireless for signals between digital signal processors (DSPs) and control panels
- Control algorithms
- Diagnostics
- Navigation – the use of gyros to keep CMs on straight headings
- Imaging ahead of mining – having accurate three-dimensional views of the coal seam, especially for super panels that run the greatest risk of having anomalies and washouts
- Horizon sensing – the ability for the machine to detect, identify, and respond to the coal seam horizon

Cutting coal in underground mining can be a hazardous operation. Hazards include exposure to methane liberation, coal and rock splintering and outburst situations, airborne dust, and considerable noise. While systems are in place to reduce these hazards, it’s generally agreed that the more remote the operators can be, the better. However, remote locations have the disadvantage in that the operator cannot see the bits actually cutting the coal and therefore does not have full control of operation.

Additionally, roof and bottom conditions are greatly impacted by how the coal is cut. Conditions can vary greatly from mine to mine, and some operations cut “rock to rock”, while others want to selectively leave roof coal and some bottom coal. Given the growing focus on producing cleaner coals, some mines selectively cut horizons to leave behind a greater percentage of waste rock, and even lower quality coals that may contain greater percentages of ash, sulfur, and even trace metals. Unless the operator is close to the cutting, it is virtually impossible to see the various horizons and direct the cutting accordingly.

1.3 Smart Mining with the Horizon Sensor

Stolar initiated a multi-year process of developing the Horizon Sensor (HS) technology to advance the concept of “smart mining”. To achieve horizon detection, Horizon Sensor units deploy a combination of electromagnetic (EM) science, high-tech processors, and control software. The EM technology can continuously transmit and receive radio signals that provide data and readings that are converted to digital outputs and transmitted via wireless communication to the control box that includes a GUI for the operator.

A Horizon Sensor is mounted in the cutter heads or cutter drums of the mining machine inches from where the actual cuts are being made. In general, the cutter drum is outfitted with two interconnected enclosures. The first houses power-generation systems and control electronics; the second contains the antenna structure. The electronics are sealed within an explosion-proof (X/P) housing that resides within the inner cavity of the cutter drum, and are protected from vibration and impact. This location is different from where other horizon sensing products have been mounted. However, these other products have not been effective, in part because they have been mounted on the back section of machines. These products have not been able to achieve meaningful readings from such remote locations.

The HS is based upon the physics principle of the Resonant Microstrip Patch Antenna (RMPA). When the horizon sensor (RMPA) is in close proximity to the air-coal interface, the RMPA impedance (Z-in) strongly depends on the thickness of uncut coal. The antenna structures measures the electrical properties of the coal seam for use in estimating the uncut roof and floor coal thickness. The sensing element radiates into the coal face continuously throughout the cutting cycle. Measurements are made with the element in momentary contact with the coal and transmitted to the GUI several times per rotation for analysis. The application of the sensor is illustrated in Figure 1.3.

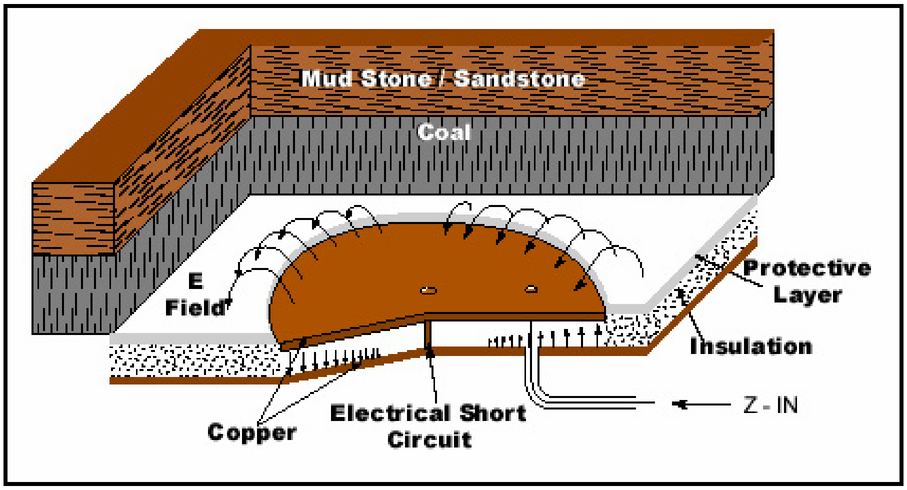


Figure 1.3. Crosscut of Resonant Microstrip Patch Antenna

The impedance is measured by the computer-controlled electronics and then sent by radiowaves to the mining machine, as schematically shown in Figure 1.4.

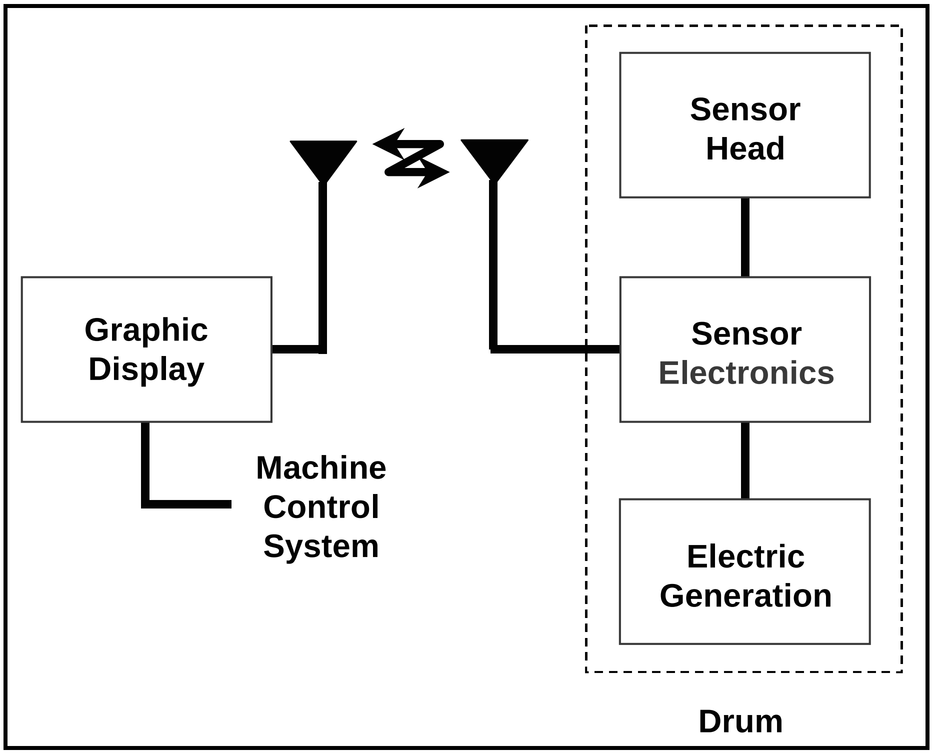


Figure 1.4. Block diagram of horizon sensor system

Stolar had to employ a collaborative research and development strategy to develop the complex hardware, software, and communication system. Its R&D partners included NASA, Sandia and Los Alamos National Laboratories, and the Institute for Measuring Systems Research (NIIIS)-the Russian advanced technology center.

The Horizon Sensor technology has undergone evaluation at over a dozen mines. The early development of HS-1 was the testing carried out at a Sasol underground coal mine in South Africa. Through two separate trials in August and October 2000, the team identified design and operational improvements for the HS-1. This effort led to a reconfiguration for ease of installation and maintenance, as well as mechanical design aspects for long-term, trouble-free operation. Additionally, the current design, termed HS-3, underwent accelerated, life-cycle testing at Sandia National Laboratories. The laboratory traditionally tests and proves the design of nuclear weapons and space vehicles requiring absolute reliability. Sandia can essentially test and certify the life expectancy of a component. Stolar management decided to leverage Sandia's testing capability to ensure high performance of the HS unit. The results of these experiences have aided the development of HS-3 for commercial applications.

1.4 Initial Economic Value Estimates

Independent analysis and case studies show that there are three places where Horizon Sensors can be valuable. Although the sensors are only used on mining machines, they bring value to the mine, preparation plant, and power plant.

"In the mine" is the first location coal executives think of when a discussion centers on cost reduction or production increases. There are a number of economic benefits to the "in-mine" use of Horizon Sensors. These include:

- Horizon sensing allows the operator to reduce waste and improve run-of-mine (ROM) quality; this benefit can be considered either cost reduction or volume increase, or both.
- Longer bit life. Keeping the bits out of rock will cause the bits to last longer.
- Reduction in fines. Advanced versions of the HS will have bit force detection for optimum bit spacing, and operators that have better control can reduce the need for excessive cutting.
- Improved efficiency, especially for CMs, leading to an optimum cut and load cycle.

Analysis has been carried out on coal production from the Pittsburgh Seam. Although the Pittsburgh Seam has been one of the world's greatest coal resources, it has also generated considerable mine waste. Estimate and analysis show that a 1% improvement in yield over a 1-year period is worth US$75 million. The annual production from the Pittsburgh Seam is approximately 75 million tons per annum, and has an average value of US$19/t.

For a specific mine, the economic benefit can exceed US$1 million per annum. The total savings for a mine are derived from less material usage, labor savings, and most importantly, improved productivity. In a longwall coal mine, the primary focus for Horizon Sensors needs to be the longwall(s) unit(s) itself because these units represent the greatest portion of the mine production. However, improving productivity is also important because more productive sections reduce panel development time.

In the preparation plant, value is captured when a cleaner ROM coal is produced by the underground (and surface) operation. The first point of value is that the preparation plant's capacity for producing clean coal is effectively increased. Less waste into the plant means greater clean coal out. Also, a cleaner ROM coal for most plants means a reduction in processing supplies, less waste to dispose of, and less wear and tear on the plant's equipment, leading to reduced long-term maintenance costs. Analysis shows that the savings at a coal mine can be US$0.10/t over 7 million raw tons input into the plant.

Finally, there is considerable value to the end users of coal when quality is improved. This is true for both steam and metallurgical coal consumers. However, as the greatest volume of coal is in the steam market, economic benefit analysis was restricted to power plants.

The Electric Power Research Institute (EPRI) in Palo Alto, California, has sponsored considerable research investigation on the economic benefits of cleaner coals delivered to power plant operations. The EPRI CQMA modeling of quality effects on power plant economics has become quite sophisticated. Cost reductions at the power plant for ash-related items can be found in several areas including:

- Ash and waste handling systems
- Ash and waste disposal (the cost of waste disposal has been escalating as environmental regulations have become more restrictive)
- Boiler and boiler tube maintenance (a reduction in corrosive ash material will enable longer life)
- Boiler efficiency, less ash improves heat transfer dynamics within the boiler

As an example, analysis shows that for an 800MW western US coal-fired power plant, a decrease in ash content of 1.5% of total weight has an economic benefit or value equal to US$2.6 million of annual savings.

Additionally, for lower sulfur content in coal achievable in part through more selective cutting strategies, power plant costs savings include a reduction in lime usage where scrubbers are in use. Lower sulfur content can also mean the purchase of fewer greenhouse gas credits (SO2) to meet emissions limits. Actually, in some cases, cleaner, low-sulfur coals can create or generate emission credits, adding considerable value. These costs savings at coal-fired power plants are real. Evidence of such recognition includes the recently announced US$95 million DOE program for improved coal-plant efficiency.

This report outlines the developmental history of HS and describes the field installation and testing programs that have occurred during the 3-year DOE funded HS program.

2. Executive Summary

When cutting coal with mining equipment, an operator cannot always see the cutter drum and bits impacting the coal seam or surrounding strata (either on a longwall shearer or continuous miner). Thus, the mining industry will greatly benefit from a technology that provides real-time detection of the seam horizon during mining operations. At a CEO workshop sponsored by the US National Mining Association, horizon sensing was identified as one of the top industry needs or requirements to improve productivity and safety, especially as future mining will be in deeper and possibly thinner seams that have a greater degree of anomalies. Coal seam detection is also a critical enabling technology for full automation or “agile mining.”

With the aid of a DOE grant (No.DE-FC26-01NT41050), Stolar Research Corporation (Stolar) developed the Horizon Sensor (HS) to distinguish between the different layers of a coal seam. Mounted on mining machine cutter drums, HS units can detect or sense the horizon between the coal seam and the roof and floor rock, providing the opportunity to accurately mine the section of the seam most desired. HS also enables accurate cutting of minimum height if that is the operator’s objective. Often when cutting is done out-of-seam, the head-positioning (HP) function facilitates a fixed mining height to minimize dilution. With this technology, miners can still be at a remote location yet cut only the clean coal, resulting in a much more efficient overall process.

The objectives of this project were to demonstrate the feasibility of horizon sensing on mining machines and demonstrate that Horizon Sensing can allow coal to be cut cleaner and more efficiently.

2.1 Technical Summary

To increase the “science” factor in the art and science of mechanical design for mining equipment, Sandia National Laboratories offered their services in areas of structural analysis and vibration testing of the HS-3 Horizon Sensor. Cutter Drum shock and vibration measurements at CONSOL yielded over 80g shock expectations for continuous miners; results were similar on a Monterey shearing machine. Therefore, the prototype HS-3 drum components were designed to withstand the levels of impact and vibrational frequencies normal to mining machines. Sandia’s assistance with structural analysis and vibration testing of the HS-3 Horizon Sensor paid off with vastly improved longevity and life span of cutter-drum-mounted modules (sensor and generator).

A Horizon Sensor Product Line was developed with expansion into alternate mining machines including the Longwall Horizon Sensor (HS-LW) and Bore Miner (HS-BM) system. Design of low-profile Battery Module has allowed installation on smaller-sized low-seam mining machines (20"–28" cutter drums). Recently permitted use of solid-core lithium batteries and Nickel Metal-Hydride batteries has extended battery pack life 500% and reduced pack size 50%.

Quality control and continued product engineering in the assembly and testing of HS-3 modules and sub-modules has increased measurement sensitivity to scattering interfaces and decreased measurement sensitivity to environmental effects (cutter bit picks, cutter-drum water spray, cut coal and dust). A dual frequency sensor (400/600 MHz) has improved Depth-of-Penetration-and-Discrimination out to 40 inches for uncut coal prediction. An additional body-mounted inclinometer was added to the system to correct mine height predictions for variation in entry slope angle and/or body movement during the cut cycle. There were also improvements in reducing the HS thermal response of sensor components, advancements in prediction software, mine height indicators, and data filtering/storage.

The most notable technical improvement was the engineering and implementation of accelerometer-based triggering methods. These accelerometers were eventually used to detect drum rotation, trigger once-per-rotation measurement cycles, and determine cutting action as a function of g-force threshold. All these capabilities were required to make the HS-3 function properly, and are cornerstones to the electrical design.

HS-Radar development has begun in March 2003 for forward-looking void detection. Although not an original technical objective of this program, “forward-looking” capabilities are being developed that will allow the HS (HS-Radar) to detect anomalies in the coal seam ahead of mining, such as dikes, faults, and abandoned mine workings. The HS-Radar prototype is being tested using a salt wall to simulate 25 feet of unmined coal seam. This work is independent of the original DOE scope of work, but is ongoing at Stolar.

During the program, Stolar also participated in two Clean Coal Technology Demonstration Programs that involved HS-equipped longwall shearers at mid-western coal mines in the United States. The first involved two Joy 4LS Longwall Shearers at Monterey Coal Company (Exxon Mobil). These shearers used a total of three HS-LW systems from July 2002 through August 2003 on two different longwall panels. The second CCT program involved a Joy 7LS Longwall Shearer at Ohio Valley Coal Company from May through September 2003. Both CCT programs were funded by cost-share structured contracts between Stolar and the mine’s respective states. These programs allowed Stolar to participate in well-structured case studies (ground-truths) of HS-derived benefits for mine production and coal quality.

2.2 Commercial Summary

Detailed monitoring of system function, user experience, and mining benefits has lead to system improvements and continued commercial opportunities. All Horizon Sensor components have both MSHA (United States) and IEC (International) certifications. RAMP approvals for underground installations has been fast-tracked for most applications due to increasing precedents in HS approvals gathered during commercial installation programs. These programs were either commercial sales, involving the monthly lease of a HS-3 system, or they were funded demonstration programs involving the implementation of HS on private mining equipment and subsequent monitoring of HS capabilities and benefits relating to clean coal issues (funding from state or collegiate agencies).

During this 3-year program a total of 14 Horizon Sensor installations occurred. These installations, both commercial and demonstrative, are listed below in chronological order. This list includes HS version, mining machine type, mine site, and mining company.

- HS-CM
    - Joy HM31, Brandspriut-1 Mine, SASOL Fuel Company
    - Joy 12CM, Monterey Coal Company, Exxon Mobil
    - Joy 12CM, Twentymile Coal Company, RAG America
    - Marietta Borer Miner, Green River Mine, FMC Trona
    - Joy 12CM, Oxbow Mine, Oxbow Mining Company
    - Joy 12CM, West Elk Mine, Mountain Coal Company
    - Joy 12CM, Monterey Coal Company, Exxon Mobil
    - SHM Low-Seam, Logan County Mine, Massey Energy
    - Joy 12CM, SUFCO Mine, Southern Utah Fuel Co.
- HS-LW
    - Joy 4LS Shearer, Deserado Mine, Blue Mountain Energy
    - Joy 7LS Shearer, Robinson Run Mine, CONSOL Energy
    - Joy 7LS Shearer, Century Mine, Ohio Valley Coal Company
    - Joy 4LS Shearer, Monterey Coal Company, Exxon Mobil
    - Joy 4LS Shearer, Monterey Coal Company, Exxon Mobil

These HS programs each meet with different levels of commercial and technical success. Some programs were more successful than others; however, all led to installation and calibration experience and continued improvements in the HS system. Program studies have shown that real-time horizon sensing is viable with Stolar's HS system and that the product line has the potential to reduce mining cost by as much as $1 per ton. Commercialization of HS is ongoing and the instrument is becoming an industry tool.

3. Experimental – HS Technical Development

3.1 First-Generation Horizon Sensor (HS-1)

Development of the Horizon Sensor (HS) technology began in 1998 and involved more than a year of radio-frequency experimentation and mechanical design before a functional prototype was ready for field testing. This initial prototype, termed HS-1, was field tested at a surface coal mine in Wyoming, USA, as well as an underground coal mine in northeastern South Africa.

The HS-1 system was comprised of many of the same basic modules as the current commercial system (sensor, display, generator, etc.). However, the size and scope of these basic components, as well as their respective housings, were very much different. The original HS-1 sensor module is shown in Figure 3.1. This sensor module included both the generator and the sensor electronics in a single package, while the RMPA was in a separate casing.

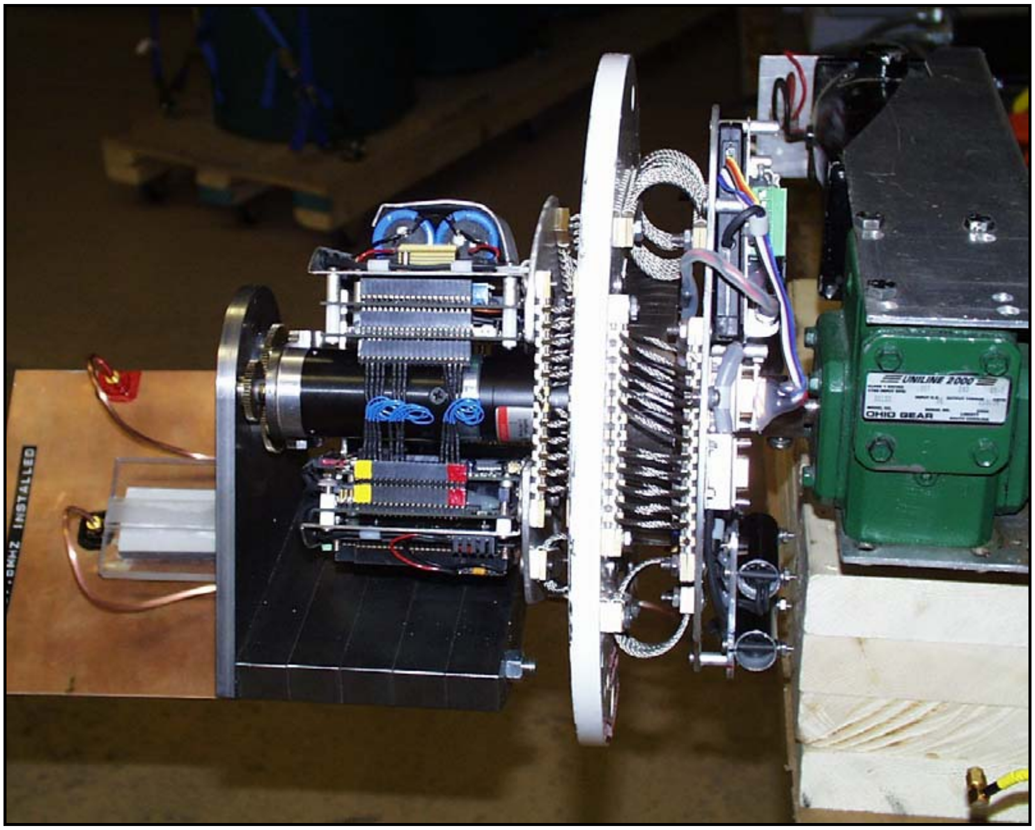


Figure 3.1. Original HS-1 sensor-generator module during early laboratory testing

These sensing electronics were designed to perform uncut coal measurements and telemeter data back to the Graphical User Interface (GUI). The HS-1 system generated power using drum rotation and a pendulum-generator concept with a DC motor. The electronics chassis rode on spring dampeners within the generator assembly. The original generator assembly was three times larger than the current design and used a DC motor with a significant swing arm-radius. Figure 3.2 shows the HS-1 generator. The generator motor was driven by a small set of brass gears fixed to the central shaft-of-rotation.

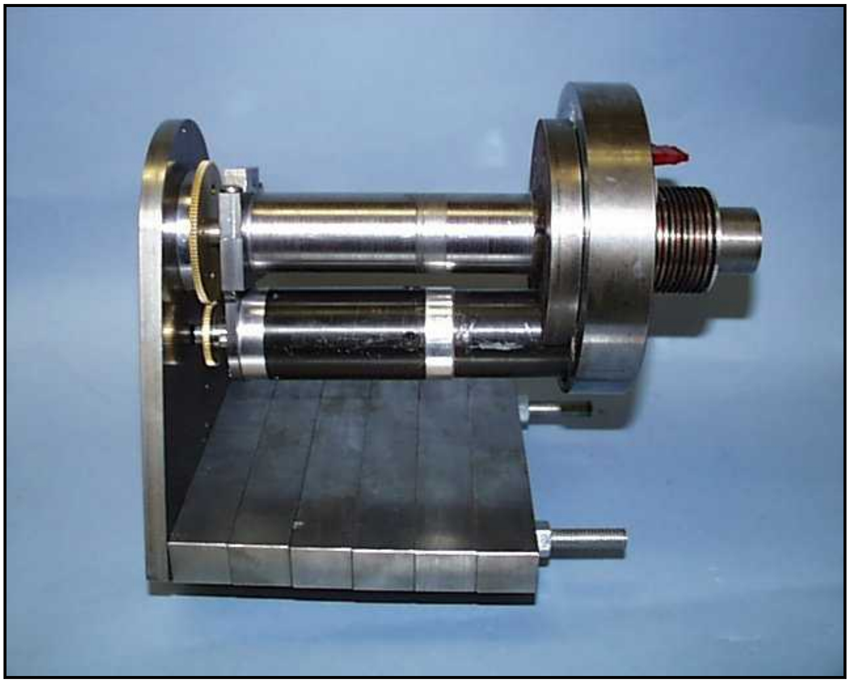


Figure 3.2. Original HS-1 generator design during early HS development (circa 1998)

The sensor-generator assembly resided within a very large Explosion-Proof (X/P) drum. This X/P drum was mounted within cutting drum of the continuous miner (CM). The RMPA antenna was housed within a small metal frame and welded to exterior of cutting drum. The sensor X/P was made Mine Safety and Health Administration (MSHA) certified. Two semi-rigid coaxial cables exited the drum through packing glands and ran to the antenna frame within the interior of the cutting drum. The X/P enclosure and its sensor assembly are shown in Figure 3.3.

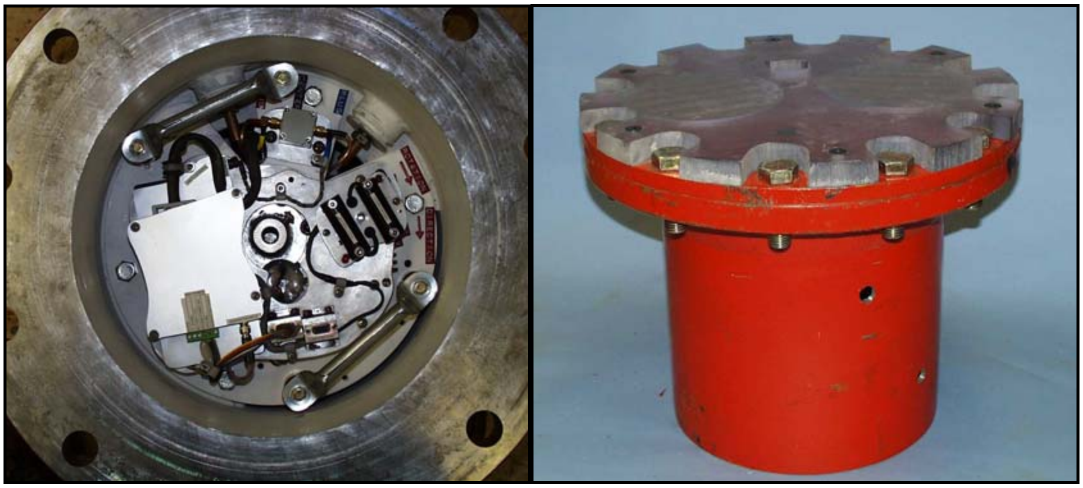


Figure 3.3. HS-1 sensor generator X/P enclosure and mounted components

The RMPA, housed within a non-X/P frame, was subject to extreme abrasion and impact. Significant testing was done to ensure the antenna frame and Lexan cover would meet the demands of the mining environment. For instance, an antenna assembly was installed on a CM at a trona mine (hard-cutting conditions) and left in place for 8 months. This antenna frame, shown in Figure 3.4, showed significant wear on the metal frame, but had less than 30% wear on its ½-inch lens after 8 months.

Figure 3.4. An original HS-1 antenna assembly after 8 months usage on a continuous miner

The HS-1 graphics display system was designed to show uncut ROOF and FLOOR coal (potash, trona, etc.) thickness on its GUI screen. The GUI electronics were also housed in an X/P enclosure, as seen in Figure 3.5.

Figure 3.5. HS-1 Graphics Display Module (circa 1999)

The system was “alpha” tested in a highwall application with limited success and several design flaws. The HS-1 system was then redesigned for mechanical packaging, better sensitivity, sampling rate, and power budget. The sensor could measure anywhere in a rotation, but focused on measurements occurring during a 10-degree “window” at top dead center (TDC) and bottom dead center (BDC) for the ROOF and FLOOR predictions. Design also began on expanding the system to other coal-cutting machine types (continuous miners, longwall shearers, and loading buckets), as well as boring machines for Potash and Trona mining (Marietta miners). The first field test of HS-1 occurred on a highwall continuous miner in Wyoming. This machine is shown in Figure 3.6.

Figure 3.6. The original HS-1 was tested on a CM at a Wyoming highwall mine

The highwall testing revealed several design flaws, including inadequate generator rigidity, poor antenna sensitivity, and poor data communication between the sensor and display; therefore, several improvements were made to the system.

The primary improvement was the advent of a new generator design (including hardware upgrades). The DC motor, along with its small pitch brass gears, was replaced with a larger AC (three-phase) motor with larger stainless steel gears. In addition, the shaft of the generator assembly was upgraded from ½-inch to over 1-inch. The final generator improvement was the addition of a front bearing assembly for the motor shaft. All of these improvements were made to ruggedize the generator assembly and reduce the chance of failure during hard coal cutting. The final HS-1 sensor/generator system is shown in Figure 3.7.

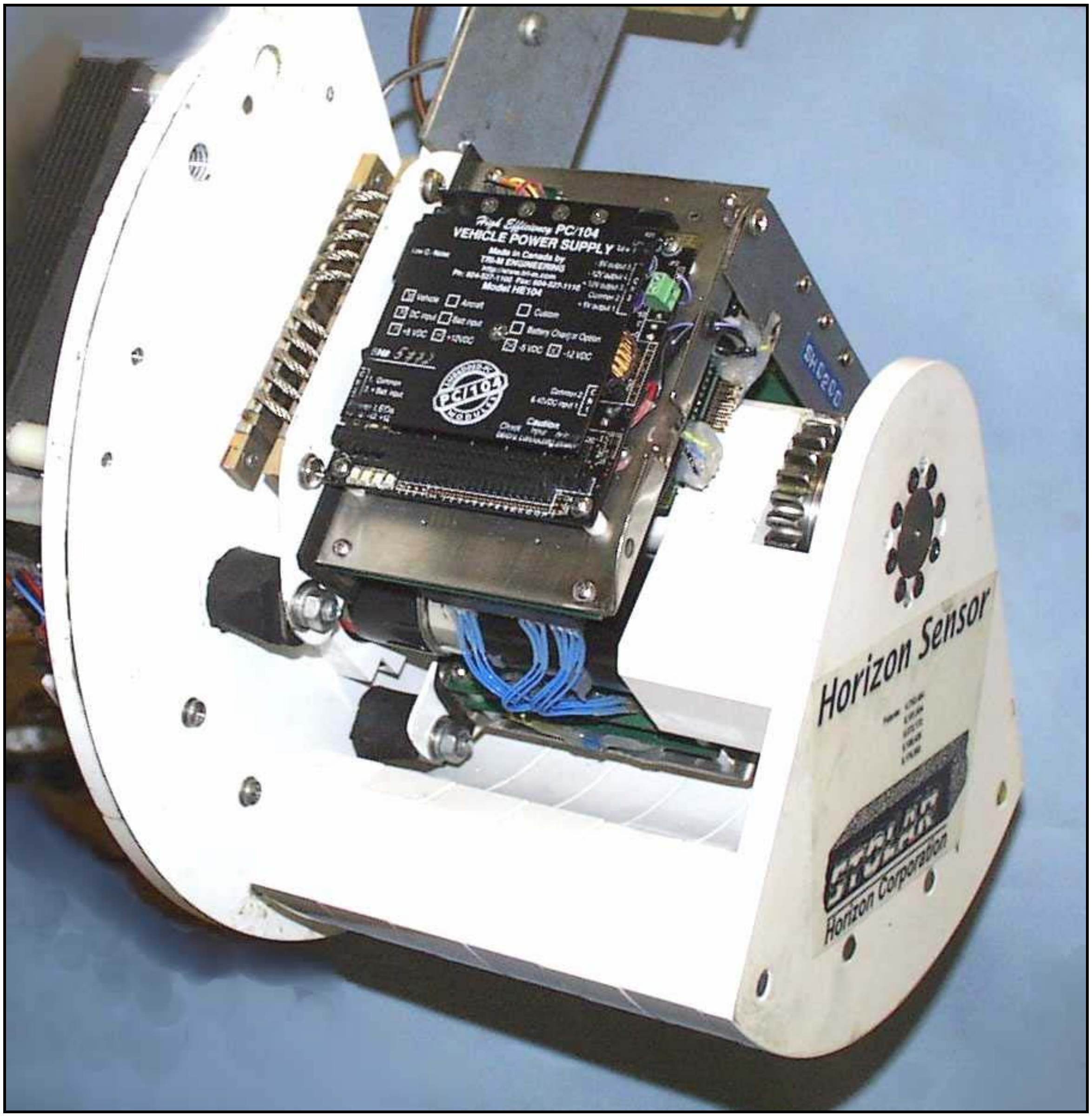


Figure 3.7. Final version of HS-1 sensor/generator system showing improved AC motor and gear assembly. The sensor chassis was also improved with stainless steel hardware and additional vibration dampening.

The final HS-1 Horizon Sensor prototype was field tested at the South Africa-based Brandspruit-2 Mine (a SASOL Coal mine) in August of 2000. The HS-1 system was installed on a Joy-based HM-31 continuous miner in an underground coal seam. These field tests were a successful proof-of-concept experiment and lead to the drafting of a list of modifications and additions to the system by the technical staffs. This list was based on the HS-1 limitations or failures in areas of performance, maintenance, longevity, and practical operation. This list was the focus of work done following the SASOL field tests by Stolar and has lead to the design and construction of improved versions of the system (HS-2 and HS-3). The HS-1 system is shown in Figure 3.8 mounted on the SASOL HM-31 continuous miner at the Brandspruit-2 Mine in South Africa.

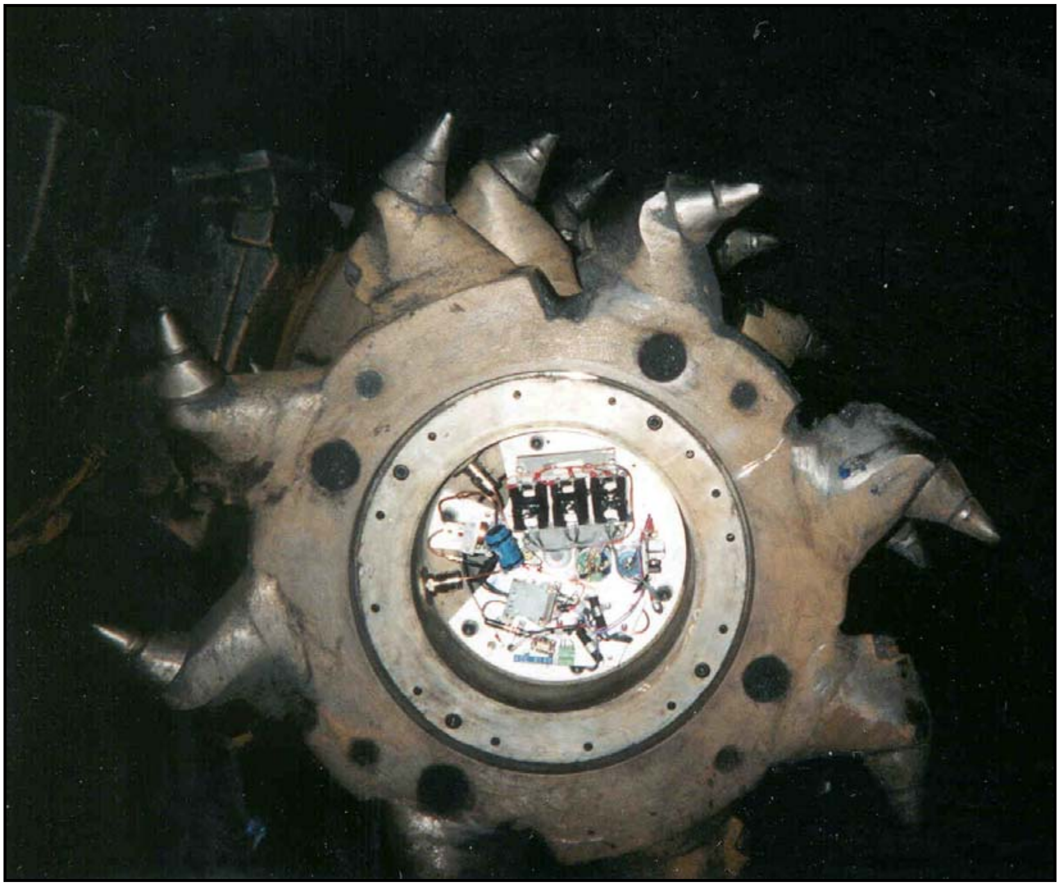


Figure 3.8. HS-1 mounted on an HM-31 miner during field testing for SASOL Coal in South Africa

The result of the SASOL demonstration testing lead to two design concepts, termed HS-2 and HS-3. HS-2 was an improved version of HS-1 using updated electronics and antennas, but using the same basic enclosures (sensor and generator together inside of cutting drum). HS-3 was a completely new design concept with sensor electronics mounted on drum surface with antenna and radically new (and smaller) generator design. The two design concepts were both initiated so that HS-2 could continue to be field tested while HS-3 was in the construction, testing, and approval phases (projected to take 18–24 months).

Both HS-2 and HS-3 would undergo similar demonstration and field testing with various coal mining companies. It was at this point that the Department of Energy (DOE) program began to partially support the HS development.

Table 3.1 shows the modification list created by the SASOL and Stolar technical staffs following the Brandspruit-2 field demonstration in August 2000. The VIABILITY column is meant to qualify the modification as being critical to the sensor's operation or a suggestion to improve performance. In addition, columns have been added to point out whether or not these modifications were incorporated into HS-2 or HS-3 design. A bold "X" in the HS-2 columns indicates that the problem was addressed and corrected for the HS-2 system design, and likewise for the HS-3 column.

Table 3.1. List of Horizon Sensor modifications or additions as of field test completion in South Africa, August 2000. The right two columns indicate which of the HS systems have incorporated/resolved the modification/problem.

Component	#	Modification/Addition/Deletion	Viability	HS-2	HS-3
GUI Display Electronics and Enclosures	1	Redesign the enclosure with a wider enter flange to allow easier access.	Suggested		X
	2	Redo switch plate for full frontal contact with plungers.	Suggested		X
	3	Move plunger to the extreme corners of the enclosure for additional internal clearance.	Suggested		X
	4	Change display screen with large prediction window and color change background.	Suggested		X
	5	Add an on/off switch to internals.	Suggested		X
	6	Incorporate isolation transformer and transient protection.	Critical	X	X
	7	Redesign power distribution board and stack in a more space efficient manner.	Suggested		X
	8	Redesign modem antenna to be an external component (certifiable)	Critical	X	X
	9	Enclosures should be Factory Mutual (Certified MSHA and SABS)	Suggested	X	X
	10	Add a COM loss indicator (LIGHT)	Suggested		X
	11	Lexan retaining plate should not be aluminum and recessed cap bolts are used.	Suggested	X	X
	12	Plungers should not be aluminum. (One brass w/ shorter travel)	Suggested	X	X
Drum Sensor and RMPA Plate	13	Coax must be secured to reduce stress on SMA connectors.	Critical		X
	14	Coax and DC Block should not restrict removal of unit from drum.	Critical	X	X
	15	Should investigate making Cutter drum an E/P enclosure.	Suggested	obsolete	obsolete
	16	Should investigate combining all electronics into single module on outside of base plate.	Suggested	X	X
	17	Should place packing glands in line (top/bottom)	Suggested		obsolete
	18	RF section should be frequency agile and controlled remotely	Critical	X	X
	19	Redesign antenna enclosure with 0-ring seal on Lexan plate and Neoprene gasket scheme behind antenna	Critical		X
	20	Redesign Generator Gear locking mechanism (D-hole w/ set screw)	Critical	X	X
	21	Investigate Modem dipole antenna efficiency.	Critical	X	X
	22	Check to see if transmission delay functions during CAL mode.	Critical	X	obsolete
Calibration and Operating Procedures	23	Realtime calibration with a remote CAL method.	Critical		X
	24	GUI Calibration procedure should include a self-resonant function which sets proper operating frequency.	Critical	X	X
	25	Incorporate a 0 to 50 cm interpolation method for a continous CAL	Suggested		X
	26	Investigate the need for separate roof/floor frequencies	Critical		X
	27	Investigate the need for dual frequencies for added discrimination	Critical		X

3.2 Second-Generation Horizon Sensor (HS-2)

The HS-1 was modified to produce the HS-2 for production Continuous Miners. The second generation HS-2 included the same pendulum weight system and AC generator as HS-1. The base plate upon which the generator/weight system was mounted was also the same.

Therefore the HS-2 required the same type and size of X/P enclosure as HS-1. The GUI used in HS-2 also remained the same with modification to the data transmission antenna only.

3.2.1 Improvements to the Power Generator

The major changes in HS-2 came in the areas of RF control circuitry and in power management. The RF sections themselves saw drastic redesign along with the micro-processor that controlled them. A photo perspective of the HS-2 is shown in Figure 3.9. Note that all the circuitry has been moved from the generator side of the base plate over to the accessory side (in radio-frequency shielded canisters).

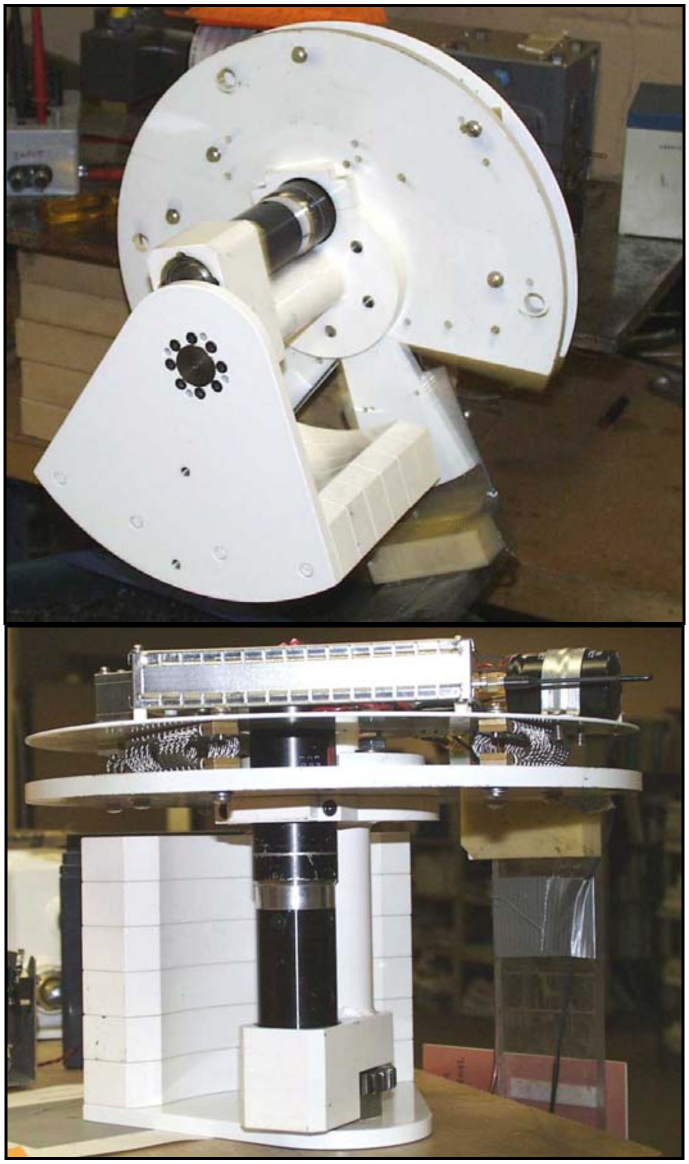


Figure 3.9. Current Horizon Sensor (HS-2). Left: Functional HS-2 spinning on the test apparatus. Right: Side view of HS-2 showing modified accessory plate

The power generation system used in South Africa has seen several improvements. These improvements lead to a major reduction of size and cost, but improved performance. The heart of the system remains the same: Maxon 250 Watt – 48 VAC Brushless motor. However, the way in which the AC voltage is rectified and regulated has changed. These changes include:

- The original 23:1 gearbox internal to the motor was replaced by a 26:1 gearbox. The main benefit was two additional Volts per revolution and this new gearbox was 1.5 inches smaller. This gearbox shaft had a key-way lock on the gear and was not susceptible to set-screw failure.
- The increased voltage negated the need for the 2.7:1 transformer. The transformer was the largest and heaviest part of the original generator system and its removal was critical to other component placement. The AC voltage was now rectified using a full wave bridge and was at adequate levels to do direct regulation.
- The HE-104 DC/DC converter was replaced by two miniature voltage regulators to provide ±12 VDC from the generator power.
- The power regulators, current limiting polyswitches, and full wave bridge diodes were combined into a new Power Conditioning Board. The regulated ±12VDC are the only voltages required by the new electronics.

The new HS-2 power generator accessories are seen in Figure 3.10.

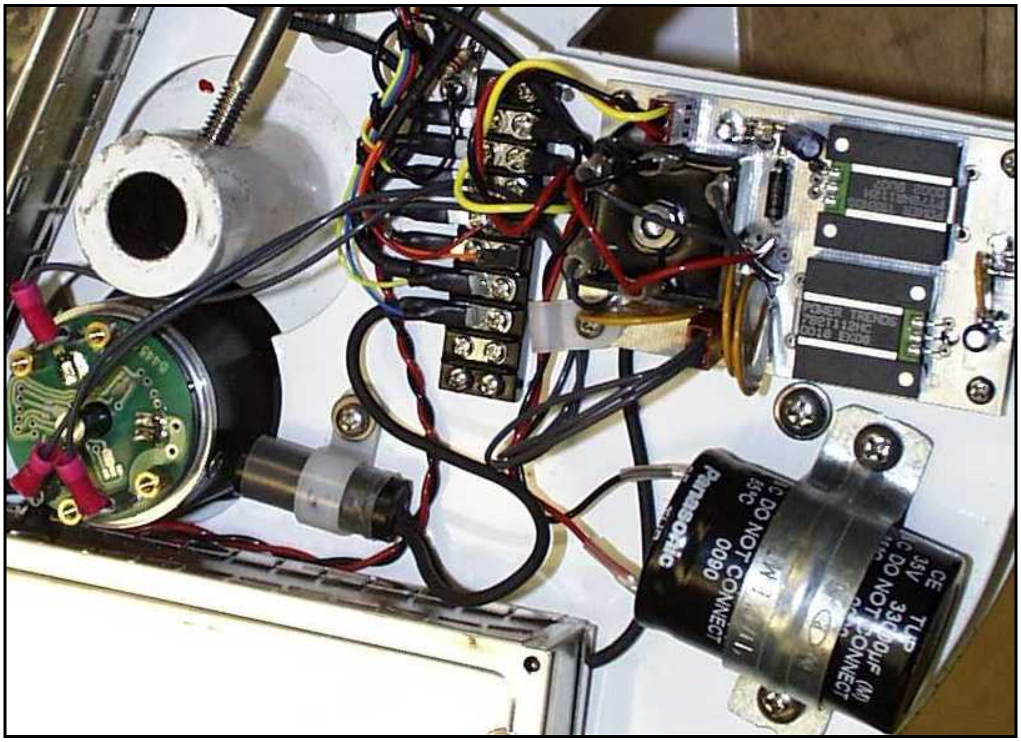


Figure 3.10. HS-2 Power Generation and Management System. Note the absence of a AC transformer and DC converter. These have been replaced by a rectifier bridge and regulators.

3.2.2 Improvements to the RF Circuitry

The PC-104 stack used in the HS-1 version was drastically changed for HS-2. The original RF board was reduced in size by 75%. The Coherent Frequency Synthesizer/Detector (CFS/D) board was reduced in size by 65% (now termed the Power Spectral Density [PSD] board). The digital interface board and HE-104 DC converter were eliminated completely. The PC-104 386 microprocessor was replaced by a miniature PIC controller. A comparison photo of the obsolete HS-1 electronics and the HS-2 electronics is shown in Figure 3.11. The major benefits of the new HS-2 RF electronics include:

- Frequency agile capability that allowed operating frequency to be set remotely or to be set automatically using a signal minimizing technique previously done with a laptop uplink. This technique was an effort to “tune” the antenna to resonance.

- Reduced power specifications for the RF section allowed for the removal of the DC-converter in favor of regulators. The new system required a fewer number of voltages and all at a reduced current. HS-1 circuits consumed 400 mA at +12, +5, and -5 VDC. The HS-2 circuits consumed only 220 mA at +12 VDC and 40 mA at –12 VDC.

- The HS-2 PIC microprocessor provided instantaneous control capabilities without the 30 second boot-up time and boot problems associated with the 386 computer used in HS-1. The PIC controller also used a meager 50 mA of +12 VDC power as opposed to the 500 mA consumption of the 386.

- The directional coupler used between the RF board and the RMPA antenna was replaced with one that exhibited less signal loss and greater stability.

- The A/D converter used in HS-2 had a wider operating range that allowed more gain to be used in the system.

- The gain of the system was then controlled internally using an active onboard attenuator as opposed to the manual potentiometer adjustments that were required of the HS-1 system.

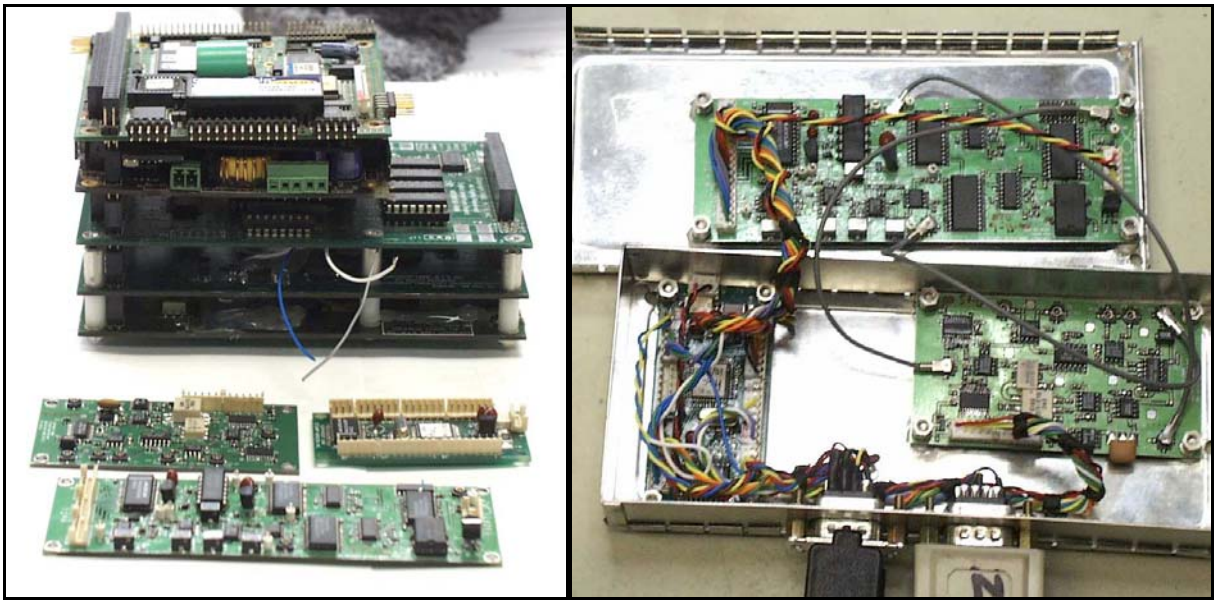


Figure 3.11. Current design of RF Control Circuitry. Left: Comparison of HS-1 circuits in their PC-104 stack to the three new boards of the HS-2 system. Right: packaging of the three new boards within a RFI canister for mounting on the HS-2 unit

The developments made in the RF section and power generation section allowed for a redeployment of material around the accessory plate. As noted, no circuitry resided on the inner (generator) side of the base plate. Everything associated with the sensor's electronics was now on the more accessible outside of the base plate. The mounting platform for all the circuitry was still referred to as the accessory plate, but several changes were made to its construction and layout. The accessory plate is shown in Figure 3.12. The changes include:

- Reduced size of components allowed repackaging of circuit boards and relocation of package from generator side of base plate to the more accessible outer side of the base plate. This allowed quicker access to the circuits for testing, maintenance, or replacement.

- Installation of RF modem and modem filter/delay circuit into its own RFI canister. This reduced the noise on the measurements resulting from data transmission frequencies and harmonics.

- Construction of a larger accessory plate surface that contained all the RF canisters, power management circuitry, and triggering switches. This plate was removable in one piece and was installed over the base plate after the base plate was secured.

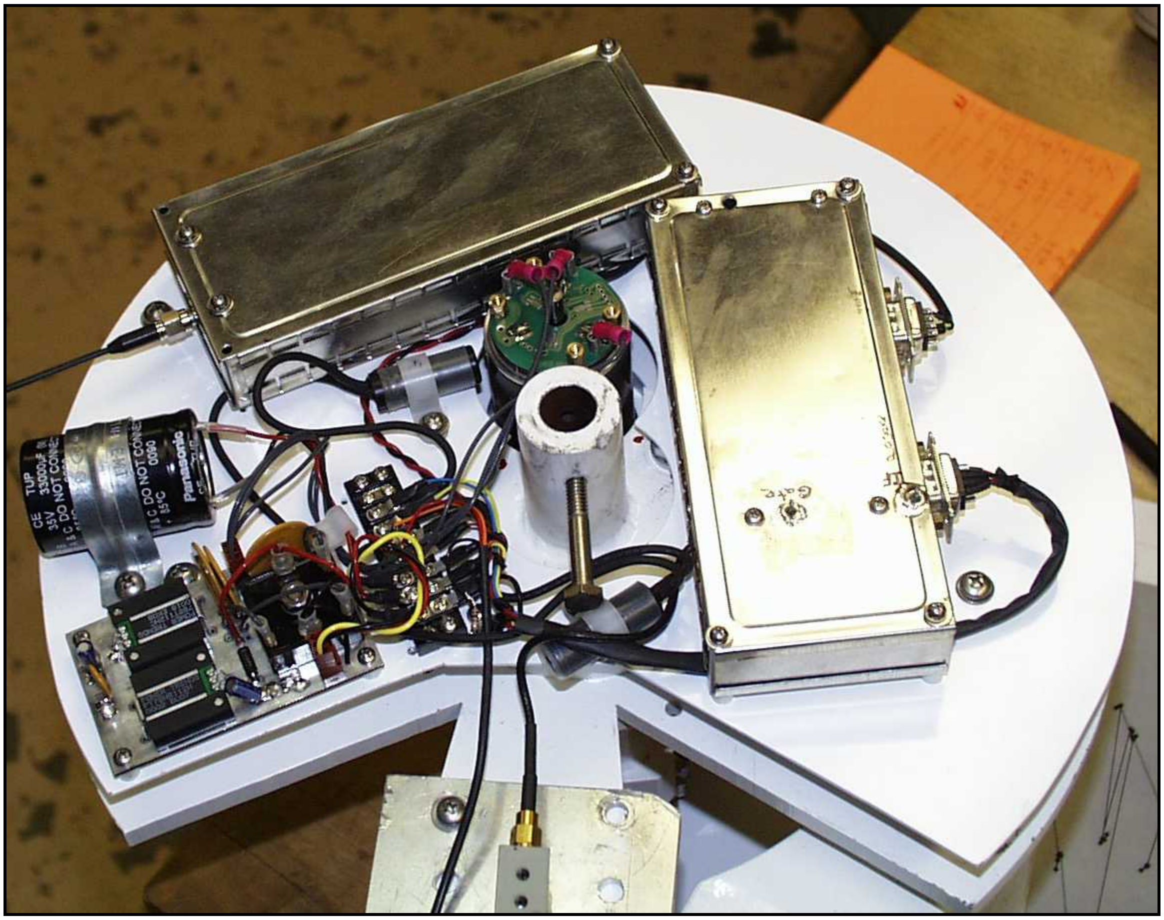


Figure 3.12. Layout of the HS-2 accessory plate. The plate contained an RF circuit canister, a modem canister, the trigger switches, and the power management circuits. The plate was easily removed by taking out the spring isolator bolts.

The DC barrier blocks were relocated to positions under the accessory plate in a manner that placed them immediately opposite of the packing glands. In this position, the semi-rigid coaxial leads did not have to be bent for installation. The lines crossed each other en route to their respective blocks and continued after the block onto their canisters over RG173 cable.

3.2.3 Improvements to the RMPA Antenna and Plate

The patch antenna mounting plate used for HS-2 was also redesigned to better protect the RMPA during use. This added protection comes from increasing the Lexan plate from 10 mm to 25 mm. The exit holes for the coaxial connectors were also reduced in diameter to reduce the area of unsupported antenna material around the connectors. A photo of the antenna plate is shown in Figure 3.13. The plate dimensions were smaller and allowed for more versatile installation. The antenna material used was still the thermally stable TMM-10 ceramic substrate, but with a thicker copper layer for improved connector mounting.

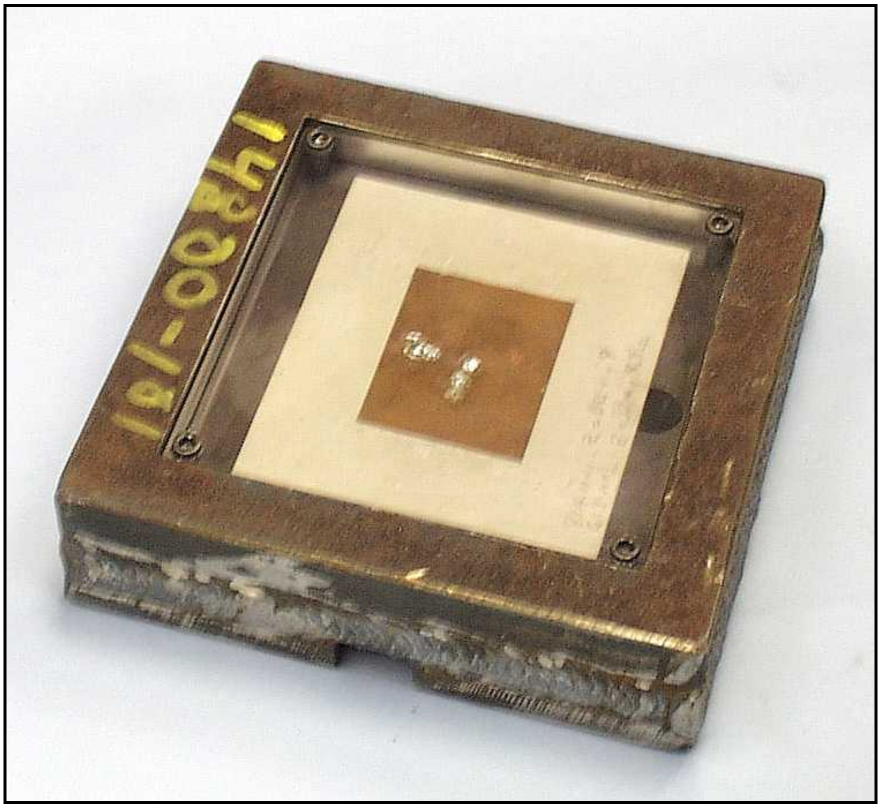


Figure 3.13. HS-2 antenna plate showing the increased thickness (10 mm to 25 mm) of the Lexan cover plate

3.2.4 Improvements in the Graphical User Interface

The basic assembly and components used in the HS-2 Graphical User Interface (GUI) were the same as HS-1, but with some improvements in performance. The improvements include:

- The addition of a data transmission antenna that exited a packing gland on the enclosure and was mounted on the body of the miner in the form of an intrinsically safe (I.S.) antenna.
- The removal of the power rectification circuit to eliminate floating grounds and computer problems. This meant that 10-40 VDC power with 2-amp capabilities needed to be routed or created somewhere on the miner prior to entering the GUI box.

The software upgrades allowed for the resonant frequency and gain settings of the RF control circuitry to be done either remotely using the GUI as an interface, or automated and initiated using the GUI. The resonant frequency was set using a predetermined “center” frequency around which the system moves the frequency over a limited range until the signal was minimized to effectively achieve resonance. The settings for center frequency and search range were still done using a laptop uplink to the PIC controller, but this did not have to be done in the mine or while the sensor was on the CM.

An automated calibration procedure was not yet possible for HS-2; the calibration for this unit was done manually. However, software improvements did begin at this point so that a GUI-initiated command would log cutting data from any point in the coal seam up until a maximum CM boom angle is reached. The GUI would store I/Q measurements taken at multiple coal thickness values based on manual thickness observables. The data transmission feature of the wireless modem link between the sensor head and the GUI was modified to include multiple transmission events per measurement. This improved data reception efficiency and eliminated "dead spots" in the data stream.

3.2.5 HS-2 Prototype Testing

All of the HS-2 design changes lead to reduced system cost, assembly time, and improved system performance and efficiency. The HS-2 was installed and tested in the US for CONSOL Energy on a Joy 14CM15 at Enlow Fork Mine in Pennsylvania. The timeline for the HS-2 system testing was as follows:

- December 9 – December 11, 2000: Stolar installed HS-2 Enclosures, Display Unit, Generator, and Antenna on CM while undergoing mini-rebuild at West Virginia shop: No RF Circuitry
- December 12 –January 3, 2001: Miner was moved from West Virginia shop to Pennsylvania mine and set up in new section: Acquired RAMP approval for underground testing. No HS-2 Run Time
- January 4 to January 8, 2001: Mining began in Enlow Fork E-5 CM section and cut about 400 ft of entry.
- January 9 to January 10, 2001: Stolar installed RF Circuits and performed minor calibration while cutting. Unit left in place with improper PIC controller software and poor sensitivity antenna.
- January 12 – January 30, 2001: CM mined nearly three shifts a day, less weekends. CM cut about 1700 ft of entries. System remained functional and was used by an operator who figured out the calibration menu and used HS-2 prediction window to keep off the floor. January 30 operator noticed no data on screen (no data transmitted from cutter head).
- January 31 – February 1, 2001: Miner continued cutting entry with functional display and non-functional drum sensor.
- February 2 – February 3, 2001: Stolar returned to replace PIC software and new antenna. Found system non-functional due to Modem Canister breaking free of mounting plate, destroying itself. Also found AC power generator inoperable. Broken components were replaced or rebuilt and system was reinstalled underground and tested for functionality and sensitivity.
- February 5, 2001: All systems "go" and calibration work resumed. Results of calibration were pending, but day-shift foreman wants CM operators trained on

calibration during today's work. System is to be left in a useful mode of operation and monitored for several days of stability before turning over to miner operator.

The HS-2 system is seen in Figure 3.14. The drum-mounted components (sensor and generator) are housed internal to the cutter drum, while the display unit is mounted towards the rear of the miner near the operator's cab.

Figure 3.14. HS-2 system mounted on a Joy 14CM-15 continuous miner at CONSOL's Enlow Fork Mine for testing in January and February, 2001

During the testing at Enlow Fork, the system was routinely inspected for mechanical problems and part failures. Each problem was addressed immediately with real-time design changes implemented in the field. Some of the testing highlights are noted below.

The unit generated power and transmitted data during coal cutting for at least 20 days before the modem canister came apart. The operator would not have seen data on the GUI up until January 30 without a functional modem and generator, so either the motor failed independent of the modem, or they are related. It is possible that debris from the modem can coming apart could have gotten into the pendulum compartment and caused the generator assembly to become hung up or frozen in such a way as to overwork the generator. There was no external or visible damage to the motor or its gears and bearings. The generator motor is really a gearbox and AC motor combined and it appears that some part of its internals were damaged.

The antenna frame (including Lexan lens and steel plate) showed little to no wear after a month of coal cutting. There was no water in the lens assembly and the connectors on the antenna were intact. This was surprising considering the lens had only three mounting bolts left out of four.

The drum enclosure maintained a watertight seal, but rust on the flame path surface implied there was some leakage along the flange (this lead to the addition of an o-ring to the design, and the recertification of the change).

The small surface-mount components on the three RF canister printed circuit boards (PCBs) were fully intact and functional, i.e., no vibration damage. Neither was there vibration or shock damage to the power conditioning board, terminal strip, DC barrier blocks, and mercury switches.

All RF transmission lines were intact and there was no connector damage or loose SMA couplers. The RMPA material was not compressed through the connecter holes of the plate like prior designs. This was important considering the amount of rock the miner cut from the seam (12–18 inches out of the roof) and the pressure on the antenna plate.

The GUI display was fully functional and did not require any maintenance. The GUI modem cable was damaged as it ran along the machine, but it was replaced and secured against further abrasion.

The software was tested and found to perform the resonance commands without failure, and the system never lost its frequency like it was prone to do before software fixes. Five different antennas were tested for increased sensitivity (10-dielectrics @ 52,52,50,48 ohms and a 6-dielectric @ 51 ohms). We found the TMM-6 antenna to work best, but will replace with TMM10/48 ohm if floor resolution is poor.

All testing phases of the HS-2 prototype were on schedule at the Enlow Fork Mine until the vibration damping springs on the electronics plate underwent complete failure in February 2001. The resulting damage destroyed the RF sections, the wireless modem, and the power conditioning board. This halted testing and lead to the removal of the system from the mining machine.

The push for HS-3 was accelerated at this time and an investigation into the failure of the dampening springs was initiated. This investigation lead to an in-depth study of the vibration and impact forces on a cutter drum under mining conditions. The results of this study were used to design most of the mechanical components for the HS-3 system.

3.3 Third-Generation Horizon Sensor (HS-3)

Stolar Horizon's final push toward a commercial Horizon Sensor came with the design, fabrication, and testing of the HS-3 system. This third-generation system was a departure from the concepts of HS-1 and HS-2. It was similar in that it consists of a power generator, a sensor element, and a user interface. However, the packaging of the HS-3 was more modular and reduced in scope. The major theme of the HS-3 design was the creation of an antenna X/P enclosure and the separation of power generation and RF circuitry to individual modules. The overall size and weight of the required modules was cut in half and the installation and maintenance efforts were reduced. The HS-3 design consisted of three main components:

- Sensor Module: X/P enclosure housing the RMPA antenna, the RF control circuitry, the modem, the power management circuitry, and the trigger switches.

- Generator Module: X/P enclosure housing the AC generator and pendulum weight assembly.

- GUI Module: X/P enclosure housing the display electronics and modem.

The HS-3 modules were much smaller and lighter than any used in HS-2 and provided for a less intrusive installation on the CM.

3.3.1 Description of Sensor Module

The Sensor Module was a self-contained enclosure that housed both the RF control circuitry and RMPA within a single container. A drawing of the Sensor Module is shown in Figure 3.15. The RMPA and circuitry is stacked together on spring isolators and rides beneath the Lexan cover. The electronics are removable by detaching the bottom cover. The Lexan cover is a flameproof lid, which itself is replaceable by detaching the top retaining plate. A packing gland in the bottom cover routes the 3-conductor power cable into the enclosure.

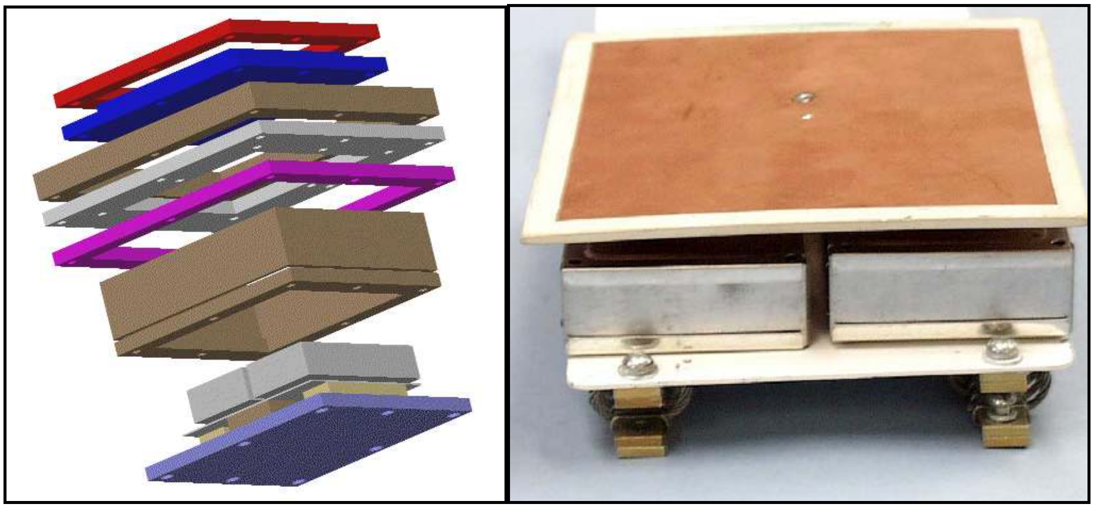


Figure 3.15. Sensor Module for HS-3 showing an exploded view of the enclosures various flanges and covers (left). The RF and Modem Canisters are mounted, along with the RMPA, within the enclosure (right).

The Sensor Module was intended to be inserted through an 8.5-inch x 8.5-inch hole cut into the cutter drum wall. The Lexan aperture is 6.5 inches square and the steel from is 10.5 inches square. A bolt ring was welded onto this hole and the module bolted to the ring. The upper plate containing the Lexan cover could be set at any height above the drum circumference and the remainder of the modules height would hang down into the cavity of the cutter drum. The body of the enclosure housing the electronics was 8.5 inches square. Its total height was 4.67 inches, but only 2.67 inches lay below the mounting flange. The RF and Modem canisters for this design, as well as the RMPA antenna, were the same as those used for HS-2. This design simply eliminated the need for semi-rigid coaxial transmission lines and made the RF electronics with antenna easier to install and replace. The RF control circuitry functioned just as it did on HS-2.

3.3.2 Description of Generator Module

The HS-3 power generation system could be housed within its own enclosure and placed within the drum cavity on either the drum cover or suspended at the hub. The type of enclosure was similar to that used on HS-2, but reduced in size and weight. The motivation for this size and weight reduction came from the introduction of a smaller generator. The Maxon Motor used in the HS-3 was still a 3-phase brushless AC type, but was rated to 80 Watts instead of 250 Watts (used in HS-2) and was less then half the size and weight. Figure 3.16 is a comparison photo of the two generators.

Figure 3.16. 80-watt HS-3 power generator (bottom) and the 250-watt HS-2 generator (top)

The HS-3's 80-watt generator had a 86:1 gearbox onboard and a higher volt-per-revolution rating than the HS-2 generator. This increased voltage, combined with the reduced power needs of the new RF circuitry, lead to a reduction in the pendulum weight needed to produce system power. This generator was tested under circuit load to verify that it could produce system voltage and current demands between 48 and 60 RPM. These verification tests proved that the smaller generator system could provide 500 mA of current at nearly 12 VDC with minimal torque to the motor.

A new pendulum system was designed to reduce the pendulum length and mass and ride at an acceptable angular deflection during operation within a CM. The external gears that were required on HS-1 and HS-2 were also eliminated from the design because the pendulum weight itself drove the generator directly. Figure 3.17 is a drawing of the HS-3 generator system and its smaller enclosure.

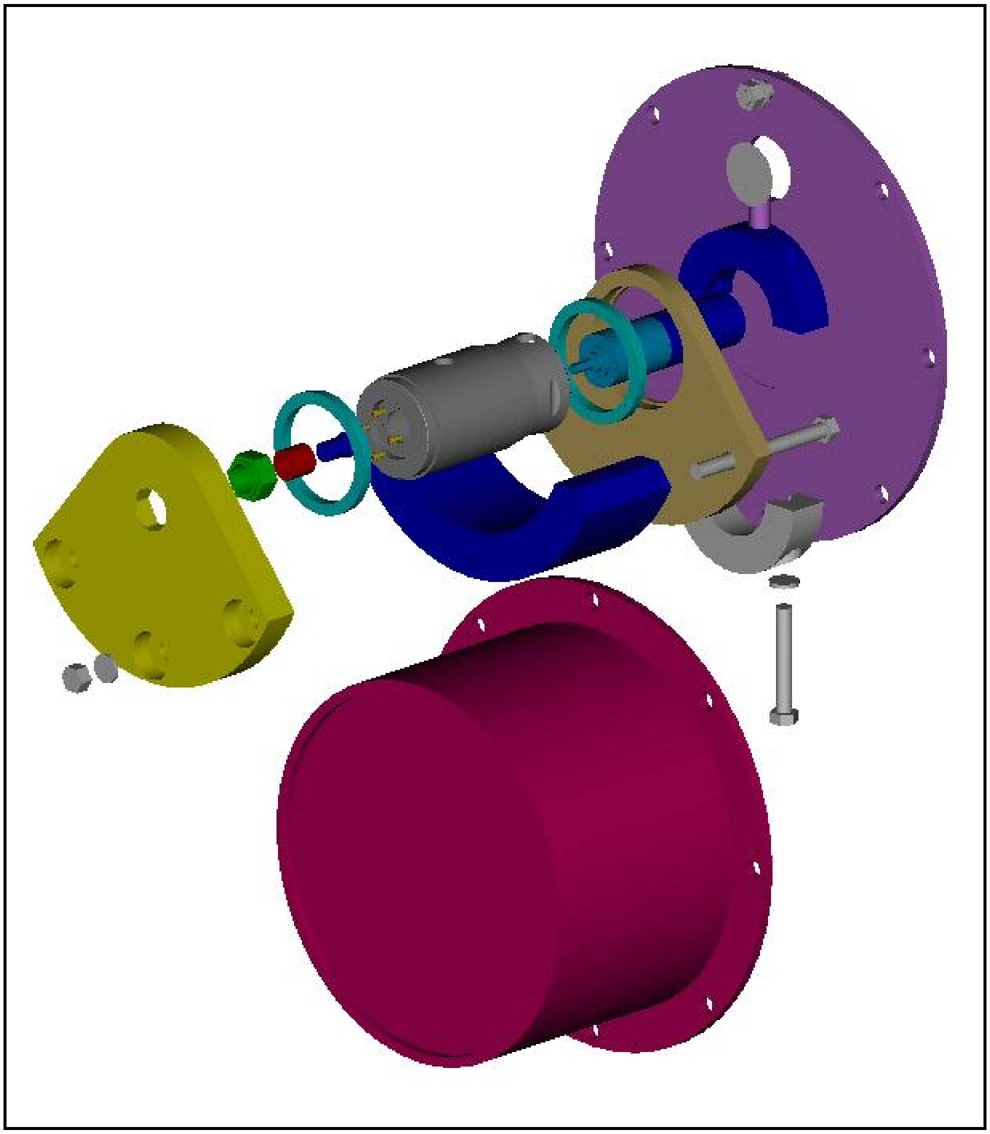


Figure 3.17. Power Generator Module. The smaller generator's increased output and reduced torque allows the HS-3 pendulum assembly to be much smaller and lighter than the HS-2 system.

The HS-3 Drum Enclosure was 21.6 cm outside diameter (OD) and 14.6 cm tall. The bolt flange was 29.2 cm in diameter and the wall thickness was 6.5 mm. Therefore, the external volume based on these dimensions was only 5344 cm^3. This was an 80% volume reduction over the HS-1 and HS-2 enclosures of 34,000 cm^3.

The motor was protected from exceeding the maximum input speed by a one-way roller clutch system. If the weight lifted over center, the clutch disengaged, preventing the motor from exceeding speed limits. The pendulum weights and the center weight total 7 kg, 69% less than the HS-2 weight system. The actual demand of the electronics was 400 mA, but at 60-rpm input and 1-Amp draw, the weight was projected to rest at 65 degrees. At 500 mA the weight was projected to rest at 27 degrees.

3.3.3 Description of GUI Module

The GUI module for HS-3 retained all the major electrical components as used in HS-2, but was reduced in size and had a more space-efficient layout of the electronics, modem, and display. Figure 3.18 is a drawing of the HS-3 enclosure design.

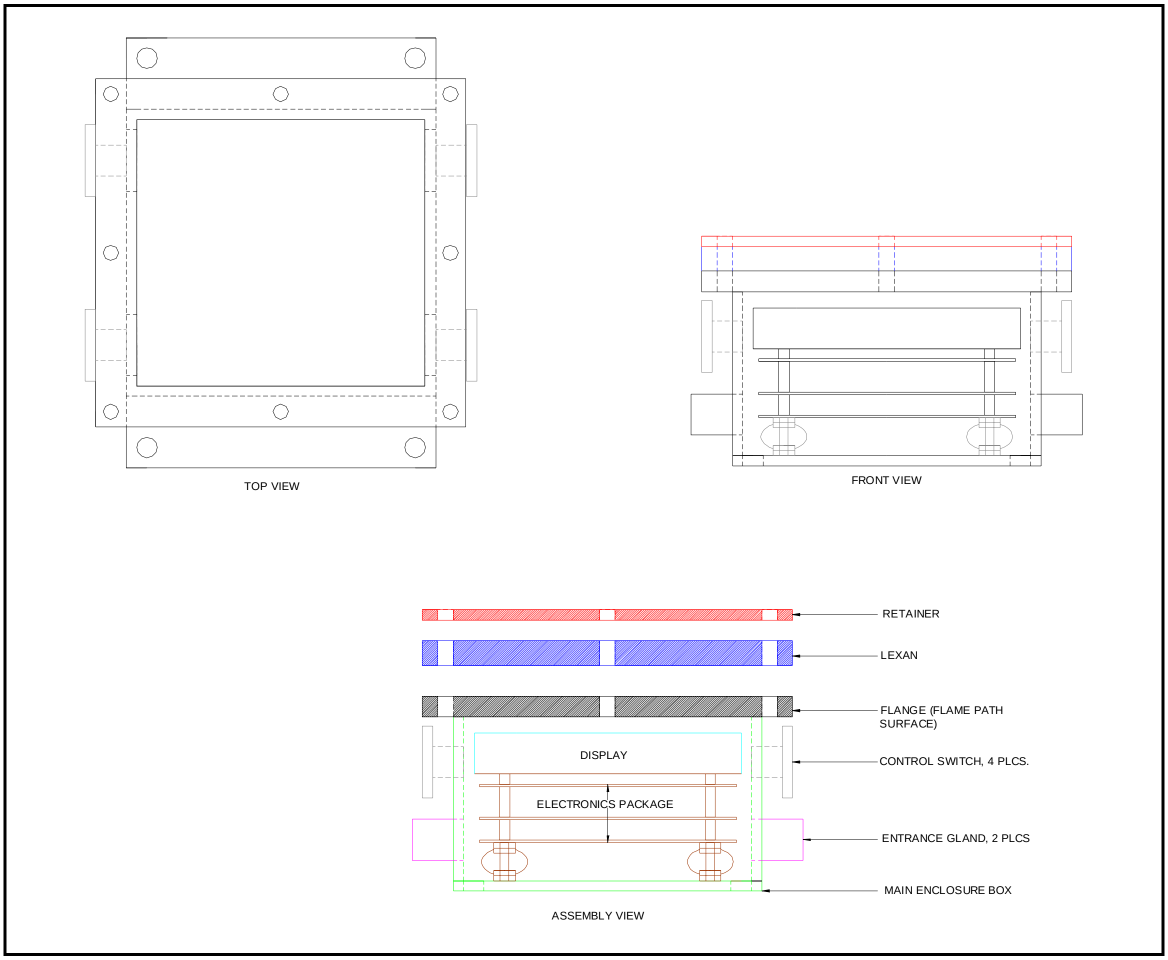


Figure 3.18. HS-3 GUI Module enclosure. The size and layout of the enclosure have been reduced and made more space-efficient.

The new features of the GUI Module include the following:

- The power distribution board was modified to include the same type of voltage regulators used in the sensor module. These regulators took the place of the HE-104 DC/DC converter and eliminated 3 cm of stack height.

- The number of packing glands was reduced from four to two. One gland was needed for power input and another for the modem antenna. The glands were placed opposite one another to allow for more space on one side of the enclosure for components.

- The position of the packing glands and the plunger switches was moved to the extreme corners of the enclosure. The switch mechanisms themselves were thereby relocated to the top and bottom side walls of the enclosure. This provided more clearance between the switches and the electronics. This also allowed the switch mechanisms to be placed in front of the plungers for direct frontal contact as opposed to the less reliable shearing contact used in HS-1 and HS-2.

- The bolt flange for the HS-3 enclosure was changed to an external design as opposed to the previous internal flange. This ensured that the enclosure's entrance from the top was the same dimension as the internal void, allowing easier installation and removal of the electronics.
- The retaining ring for the Lexan plate was made thicker and the bolt holes were counter-bored to allow for the use of cap head bolts as opposed to the original hex head. This reduced bolt-head damage and provided for certification acceptance.

The reduction in the number of circuit boards combined with the redistribution of required components allowed for the overall reduction of the GUI enclosure volume. The HS-1 and HS-2 GUI enclosure had an overall external volume of 6128 cm^3, the HS-3 enclosure was only 2982 cm^3—a 51% volume reduction.

3.4 Horizon Sensor (HS-3) Operational Theory

3.4.1 General Horizon Sensor Operation

The HS-3 calibration procedure was based on the addition of two new spatial coordinates integrated into data stream of RMPA measurements: angular coordinates of sensor position during drum rotation (alpha), and inclinometer angles of boom arm position. These coordinates allowed for the precise determination of the sensors position within the coal seam and the use of this position for calibration and automation. A calibration cycle was outlined that will follow a typical sump-in cycle for the continuous miner. This calibration cycle could be performed or repeated at any point in the system's operation, but needed to be done at least once before the HS-3 was ready to mine production coal. The calibration cycle could be broken up into discrete steps for the purpose of explaining the sequence. However, before the calibration cycle is explained it is important to know how the sensor will perform its continuous measurements and how these measurements will be divided into functional modes.

Figure 3.19 is a diagram of a cutter drum in use within a coal seam. The HS-3 is no longer taking discrete roof and floor measurements exclusively, but rather breaking the measurements (taken during a rotation) up into discrete modes of operation. These modes will perform a number of unique functions associated with monitoring position of the head in real time. The modes can be divided into four categories.

Mode 1 is a Roof/Floor Proximity Mode. The mode creates a 10-degree window about Top Dead Center and Bottom Dead Center (TDC ±50 mS) during which a predicted value of distance to the bounding rock is determined. When the arm is above the horizontal, Mode 1 will be a Roof Reading, and when the arm is below horizontal, the mode will alternate to a Floor Reading. The determination of roof/floor proximity is done using a calibration table generated during the calibration cycle comparing antenna response to distance.

Mode 2 is a Sump Depth Approximation Mode. The mode creates a 150-degree window centered on Bottom Dead Center (BDC ±750) during which a predicted value of the sump-in distance is determined. This determination is done by measuring at which angle the sensor response passes a coal-to-air transition. This transition point is the angle at which a depth of penetration for the cutter drum can be calculated. The capabilities of Mode 3 can pinpoint the sump depth between the limits of 0.05 times the drum radius to 1.95 times the radius, or 90% of the drum's diameter. Mode 2 is only active above the horizontal when Mode 1 is Roof Reading active. This is due to the conflict of measurement windows that would occur between a floor reading and a sump-depth reading.

Mode 3 is a Forward Anomaly Detector Mode. Mode 3 creates a 5-degree window when the sensor points directly forward into the Coal Face. Measurements in this window are logged during calibration and used to create a variable termed "Forward Nominal Response (FNR)." Sensor responses during Mode 3 that later deviate from FNR would be considered to have arisen from anomalous structures directly in front of the cutter drum within the coal seam, e.g., faults, dikes, washouts. Deviation level from FNR can be adjustable to create a sensitivity scale.

Mode 4 is the Data Transmission Mode. Mode 4 creates a 90-degree window immediately following Mode 2 during which all of the data measured during a full rotation are transmitted out of the sensor to the GUI. Any command originating from the GUI would also be received during this mode. Depending on data-stream density and transmission rate, several transmissions could occur during this window to ensure reception and uninterrupted communication between the sensor module and the display.

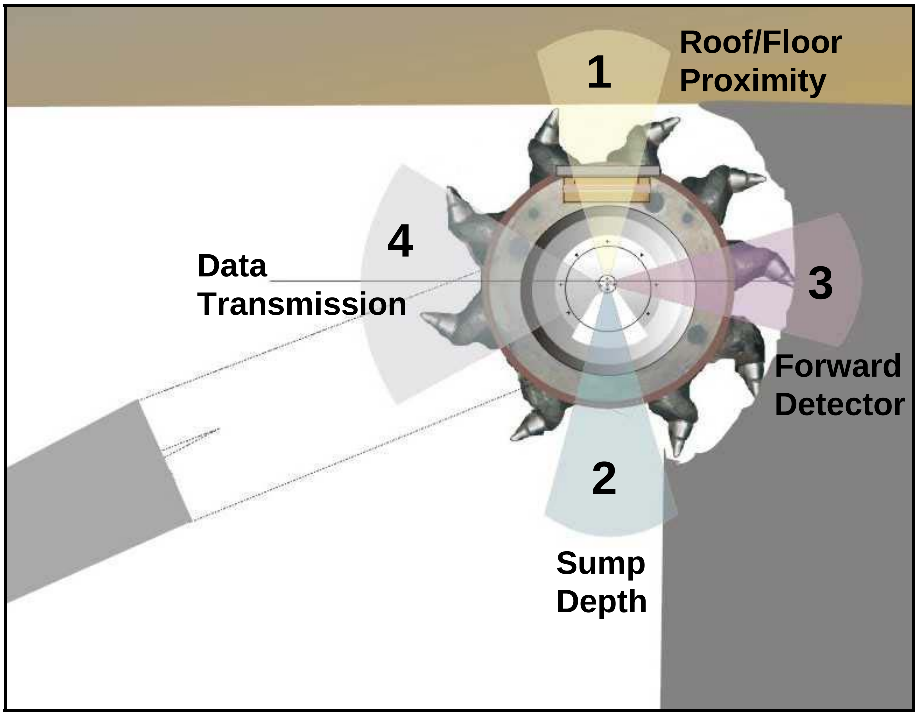


Figure 3.19. Cutter drum showing the four modes of functionality that occur during a single rotation of the HS-3 sensor

The position of the cutter drum's boom arm is critical in providing a spatial point of reference to the measurements during the calibration cycle. An inclinometer in the arm can relay angular positions to the GUI module directly, or the Continuous Miner's processing unit could even supply these values directly.

3.4.2 Standard HS Calibration Routine

The Calibration Cycle sequences are not as discrete as the drum-rotation modes, but rather flow continuously into one another. The measurement modes are dictated by inclination angle, but the sequences of calibration should be performed without pause once the calibration command is given. The calibration cycle must be performed in an area of clean, level floor rock and supported roof rock.

Using this system of angular coordinates for measuring drum rotation and drum elevation, a stepwise procedure of calibration can be outlined. The procedure is broken up into two steps: Drum Initialization and Drum Calibration.

The sequence of cutter-head motion for the Initialization Process is shown in Figure 3.20. Drum Initialization occurs using the following steps:

A) The mining machine's physical dimensions are entered into the display. These dimensions include boom length (inches), drum diameter (inches), drum rotational speed (RPM), and body pivot positions. The drum is then positioned at a height equal to the top of the miner body, and the boom position is initialized; this records the angle of the arm as the Boom Angle (θ boom). This angle is assumed to separate the floor mode from the roof mode during prediction modes.

B) Position the drum directly above the floor bounding rock (or uncut coal layer) and initialize head position. Once the calibration command is received, the angle of the arm is recorded as the Minimum Angle (θ min). This angle is only assumed to be at the level of the floor during the calibration sequence and is not involved in floor predictions after the calibration sequence is complete.

C) Position the drum directly below the roof bounding rock (or uncut coal layer) and initialize head position. Once the calibration command is received, the angle of the arm is recorded as the Maximum Angle (θ max). This angle is only assumed to be at the level of the roof during the calibration sequence and is not involved in roof predictions after the calibration sequence is complete.

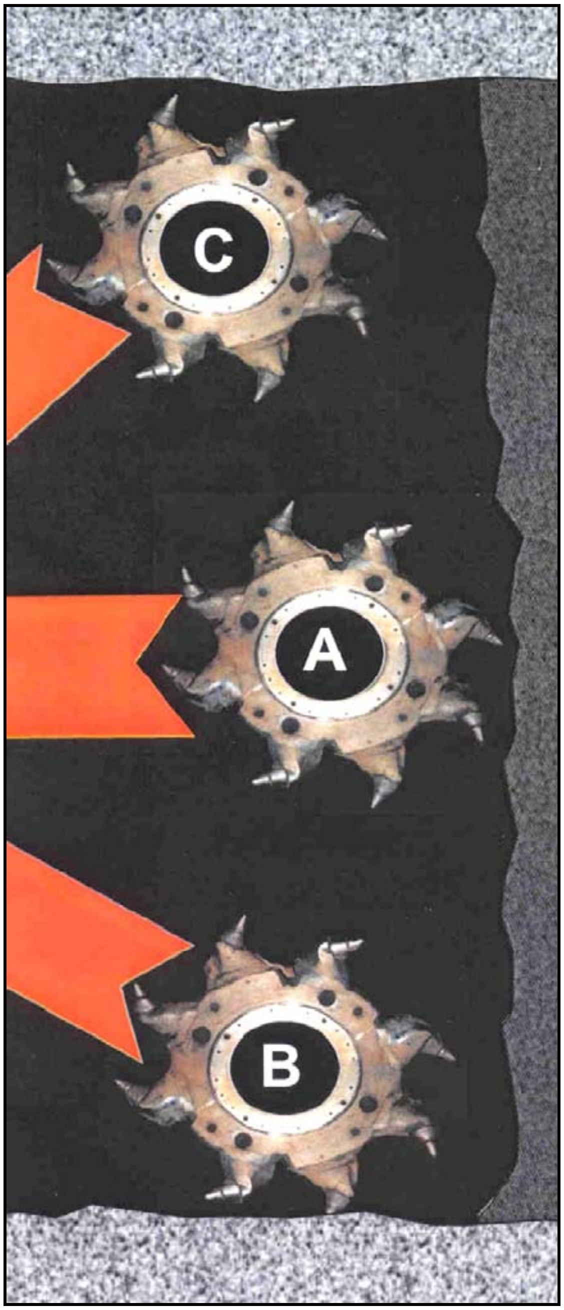


Figure 3.20. Cutter-head position for the Drum Initialization Process

Under constant rotation the cutter drum is raised to the roof at a moderate rate. Once the boom arm is above the horizontal, Mode 1 begins to measure the sensor response to the bounding roof rock. This step creates the ROOF calibration table in which sensor response is a function of arm angle (θ).

Once the drum is in near contact with the roof rock, the arm inclination reaches a level value, or Maximum Angle (θ max). The difference between θ max and θ min is the practical range of the arm's movement within the coal seam's bounding rock at that specific point. This total angular difference (θT) is related to the vertical distance traveled (Z) by the drum in Step B, and the length of the boom arm (L) by the expression Z = 2L sin(θT /2). Once the total travel distance is computed, coordinates in the calibration table of Step B can be converted from angle to distance (centimeters vertical distance per degree of arm angle) for roof/floor predictions. This value is also of use for measuring coal-seam height (T) during any sump-in cycle by the expression T = 2R + Z, where R is the radius of the cutter drum (R).

The sequence of cutter-head motion for the Calibration Process is shown in Figure 3.21. Drum Calibration occurs using the following steps:

D) Sump into the seam at mid-level. This engages the head into the seam creating a realistic environment from which to measure uncut coal while mining continues.

E) Cut up to the floor rock contact (or desired level of coal thickness) while storing the RF response to decreasing coal thickness.

F) Cut down to the floor contact (or desired level of coal thickness) while storing uncut coal thickness data.

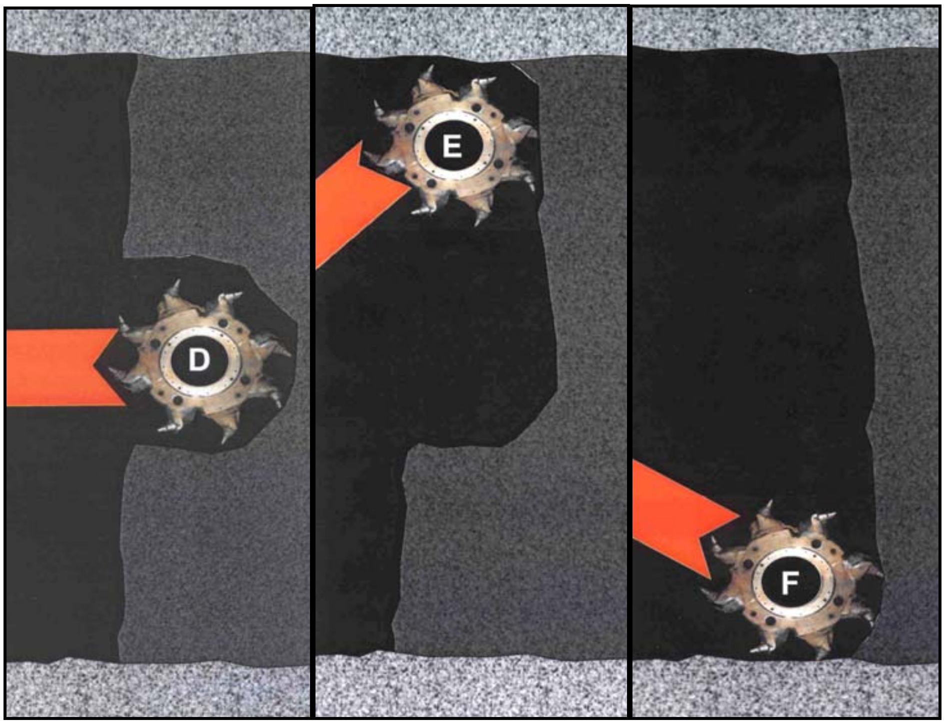


Figure 3.21. Cutter-head positions for the Drum Calibration Process

This completes the calibration cycle and at this point the GUI processor would take all the information received during every Mode 4 transmission and create the variables, constants, and calibration tables needed to prepare the sensor for normal operating use. Normal use would now consist of roof rock proximity estimates measured in centimeters of air gap, sump-in depth estimates measured in centimeters of penetration or in percent of drum diameter engagement, forward anomaly detection indicated by an adjustable warning system, and floor rock proximity estimates measured in centimeters of uncut coal thickness.

3.4.4 Mining Height Indicators

The mining height indicators are driven by two independent variables: total height of the cuts being made, and current head position relative to a user-defined “zero-point”. These are illustrated in Figure 3.22.

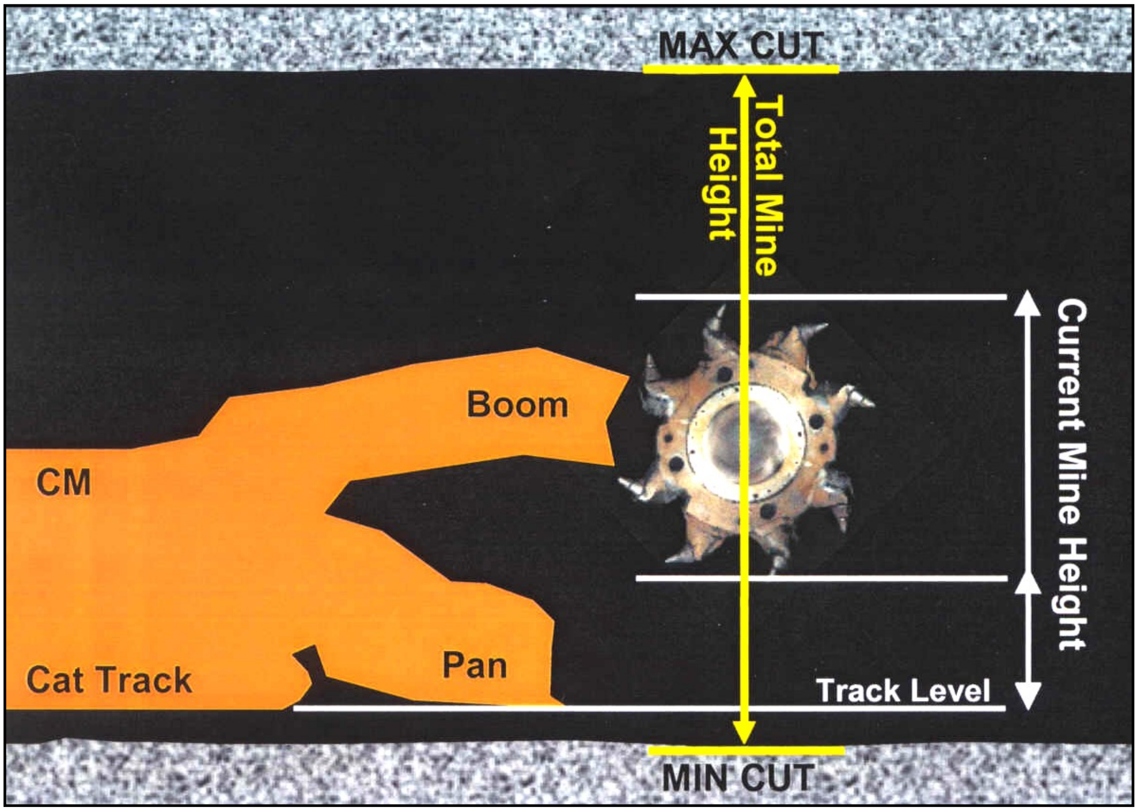


Figure 3.22. Diagram showing the definition of Total Mine Height and Current Mine Height

Current Mine Height is defined as the distance from the cutter head to a preset base level (zero-point). This base level can be set at any point by the CM operator. It can be used as a reference to the level of the cat tracks on the miner or for a desired floor level. This base level (“zero-point”) is set by the operator using SET BASE procedure.

This distance number increases as the cutter head rises. This number represents two different distances depending on cutter position above or below the middle of the coal seam; these are:

- From the floor to about mid-seam, the number given is the distance from base level to the BOTTOM of the cutter bits.
- From mid-seam to the roof, the number given is the distance from base level to the TOP of the cutter bits (bottom distance plus drum diameter).

If the cutter head falls below the base level, the number given goes to a negative distance showing how far below the zero-point the bit circle has gone. When the number goes negative, a RED dash sign is seen before the number on the screen.

Total Mine Height is defined as the distance from the minimum cut on the floor to the maximum cut on the roof regardless of the base level. This distance will update itself when the cutter head passes through mid-seam every sump cycle.

The Mining Height indicators are shown on the HS-3 display screen in Figure 3.23. The numbers for Total Height are given in feet (') and inches (") at the lower right of the screen. The numbers for Current Height are given in feet (left two boxes) and inches (right two boxes) at the top of the screen.

Menu: Main:Misc:Setup:Base
92.8, 2026.4, 1, 3
Msg: Horizontal to Base: -15 inches

Figure 3.23. HS-3 display screen showing mining height indicators (current height and total height). The number in the lower left box is the predicted uncut coal thickness in inches.

3.5 Horizon Sensor Shock and Vibration Testing

Electronics mounted near the cutting edge of mining machines are subjected to high levels of shock and vibration. However, operating shock and vibration of cutting coal and rock had not been investigated for the wide variety of mining conditions prior to this program. To increase the science factor in the art and science of mechanical design of the Horizon Sensors, Sandia National Laboratories (Sandia) offered its Center of Excellence in structural analysis and testing to this project. Sandia developed its structural analysis and test facilities in support of the United States weapons program. Like the mining industry requirements, weapons must faithfully fulfill their intended objective and be capable of flawless operation when deployed against an enemy target.

Working with CONSOL’s Enlow Fork mining personnel, a preliminary study of shock and vibration was performed on the cutter head of its Joy 14CM-15 continuous miner. During this study it was determined that the acceleration on components in the cutter drum (g-force) during coal and rock cutting was measured at 40g and 80g, respectively. Analysis of the data showed that the energy density reaches a maximum value near 30 Hertz. This frequency was related to the number of bits on the drum and the rotational speed. The HS-3 was then installed on Sandia’s shake-and-shock table. The structural resonant frequency of the electric generator and sensor enclosure were measured. Since they occurred at a much higher frequency, the HS-3 was expected to be sustainable on the mining machine. The HS-3 was then put through extended periods of vibration and shock on the Sandia tables (while under rotation and electrical load).

Prior to the endurance- and life-cycle tests, members of Sandia’s structural analysis team participated in the mechanical design review of the Horizon Sensor.

3.5.1 Preliminary G-Force Testing and Data Analysis

To obtain shock and vibration data for an operating drum miner, a recording accelerometer was provided by Sandia and installed in the drum of a Joy 14CM-15 machine at Enlow Fork. Maintenance personnel from CONSOL participated in the underground tests. An accelerometer and its associated digital recorder made measurements when cutting coal and also when cutting into the coal seam roof sedimentary rock. These data were analyzed by plotting the instantaneous g force versus the run time of the machine. The time domain data were noteworthy in that the average g force reached 40g force when cutting coal and 80g force when cutting rock. The g-force cutting drum response is shown in Figure 3.24.

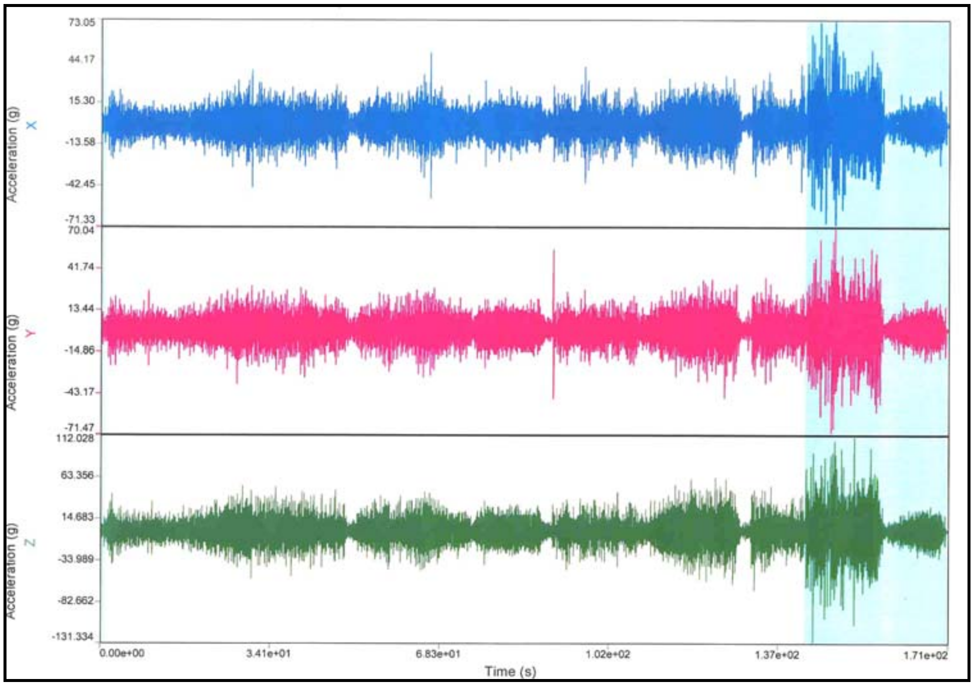


Figure 3.24. Instantaneous g force response of a coal-cutting drum

Such g-force data were routinely analyzed by Sandia in defense program work. To assist in understanding the significance of the time-domain data, the spectral density (SPD) of the time-domain data illustrated in Figure 3.24 was determined by processing in the Fourier transform. The SPD data are illustrated in Figure 3.25.

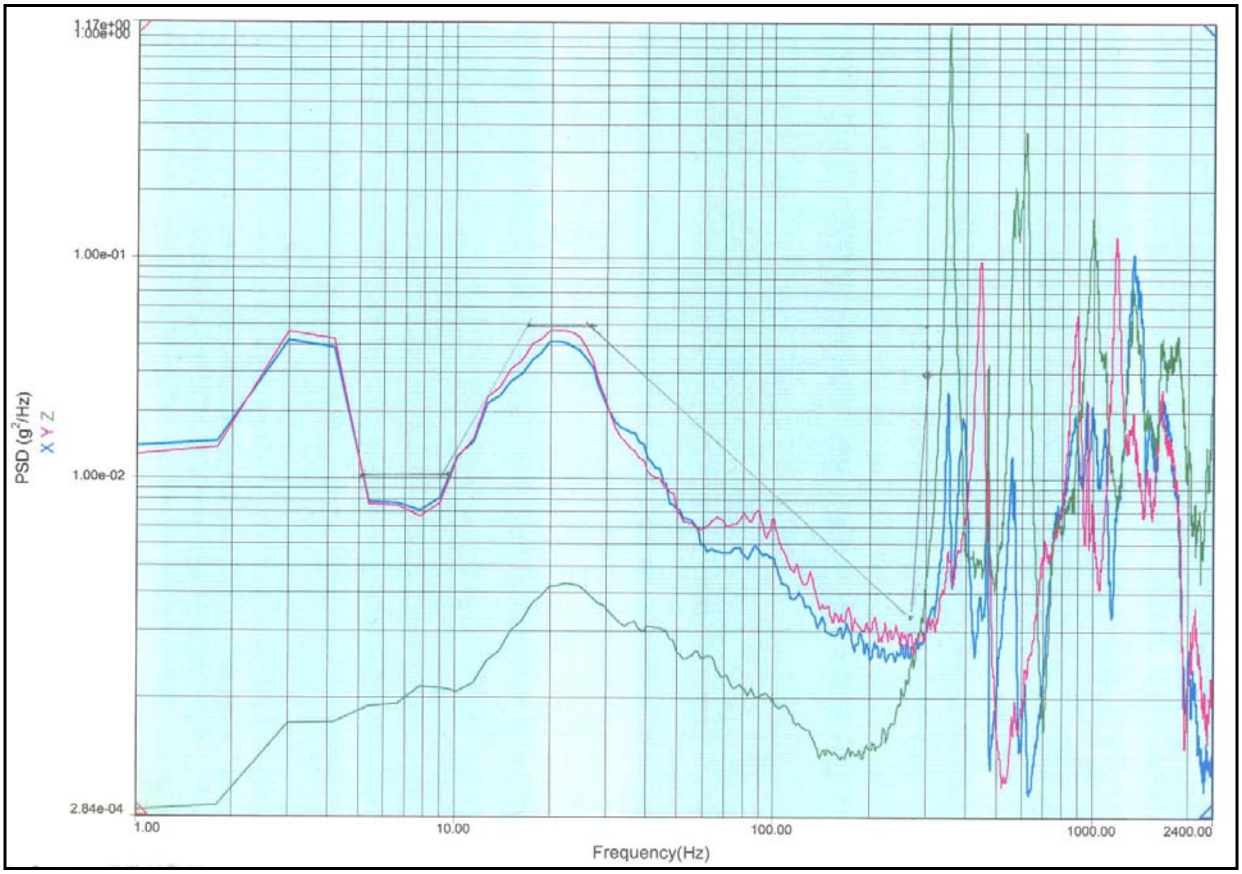


Figure 3.25. Spectral density of the 12CM cutting drum (line color code: red- input direction; green – horizontal normal to input; blue – vertical normal to input)

These data illustrated that the shock and vibration reached maximum value in the 1- to 2-Hertz and 25-Hertz bands. The frequency of maximum SPD was due to the rate at which the cutting bits strike the coal during the approximate 60-RPM rotation rate of the drum. The peak frequency of the SPD depended on the number of bits in the drum lacing pattern and the rotation rate of the drum. The mechanical design engineers used the drum shock and vibration data in their design processes.

3.5.2 Structural Sustainability Tests

Sandia's Shock and Vibration Laboratory is equipped to generate the mining machine SPD during endurance test. To facilitate the simulation of this mining profile on the HS-3 drum-mounted components, the sensor and generator modules were mounted on a rotating frame that itself was bolted to the shock-and-vibration table. The rotating frame and HS-3 components are shown in Figure 3.26.

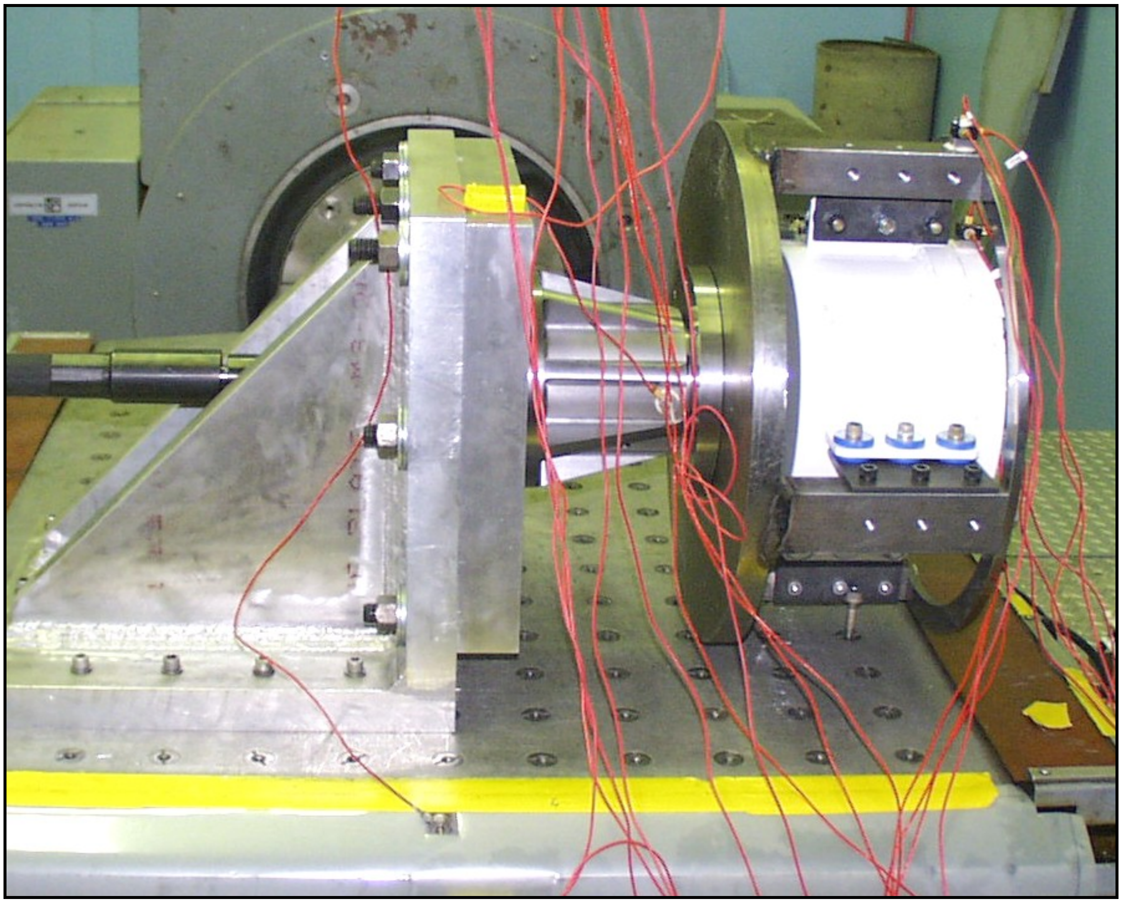


Figure 3.26. Rotating frame and horizon sensor

Accelerometers were mounted on the frame and HS-3. A real-time feedback control feature in the shock-and-vibration machine ensured that the frame SPD was recorded during the test and evaluation time period. Additional accelerometers were installed on HS surfaces of critical importance. They included the electric power generation components and electronic modules.

The structural analysis of the HS-3 components when subjected to the SPD was greatly enhanced by the graphical format of the measured accelerometer data. The frequency domain data measured on the surface of the electric power generator flameproof enclosure are illustrated in Figure 3.27.

The generator enclosure was designed with shock-and-vibration suppression mounts for the purpose of establishing the natural resonance frequency of the flameproof enclosure. The frequency domain response exhibited the attenuation characteristics of a low pass electric wave filter. The peak of the response near 60 Hz corresponded to the natural resonance frequency of the mechanical assembly. By changing the stiffness of the shock-mount material, the natural resonant frequency could be moved to a higher frequency. Stiffening the shock mechanism achieved this goal. The stop baud of the “filter” above the natural resonant frequency attenuated the shock and vibration SPD at the rate of 20 dB per decade. Measurements were made on the pendulum of the DC generator. The SPD for the pendulum is shown in Figure 3.28.

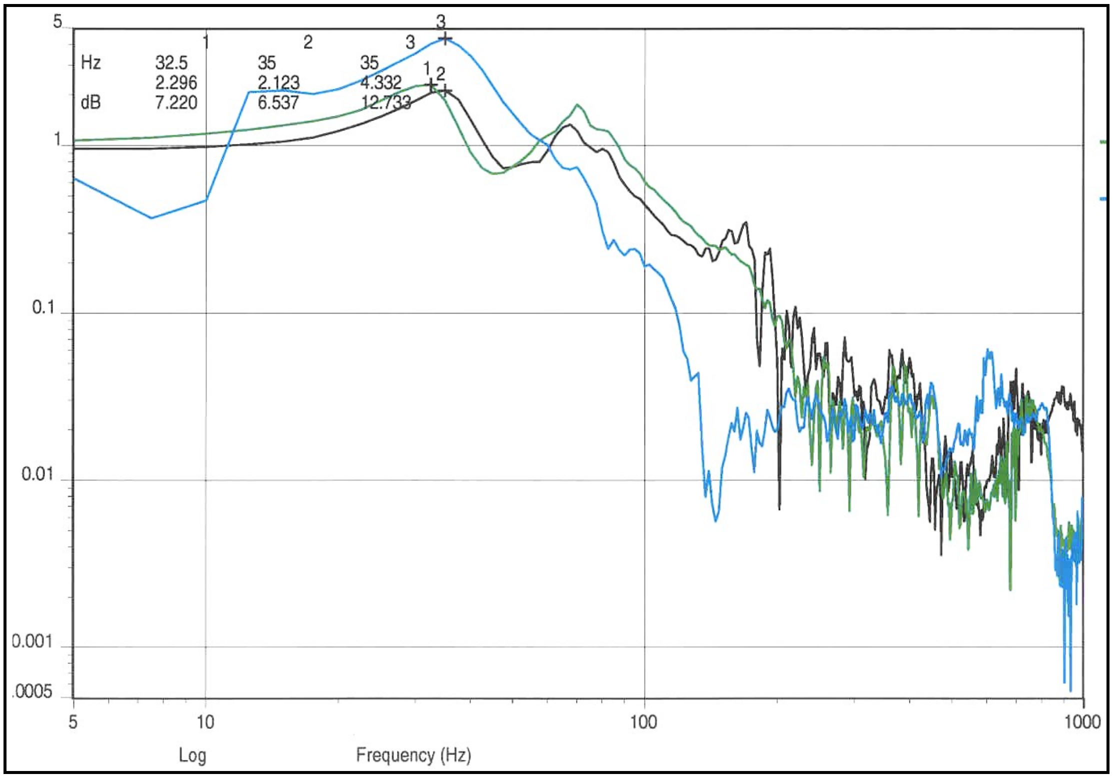


Figure 3.27. SPD response of the flameproof enclosure (line color code: black- input direction; green – horizontal normal to input; blue – vertical normal to input).

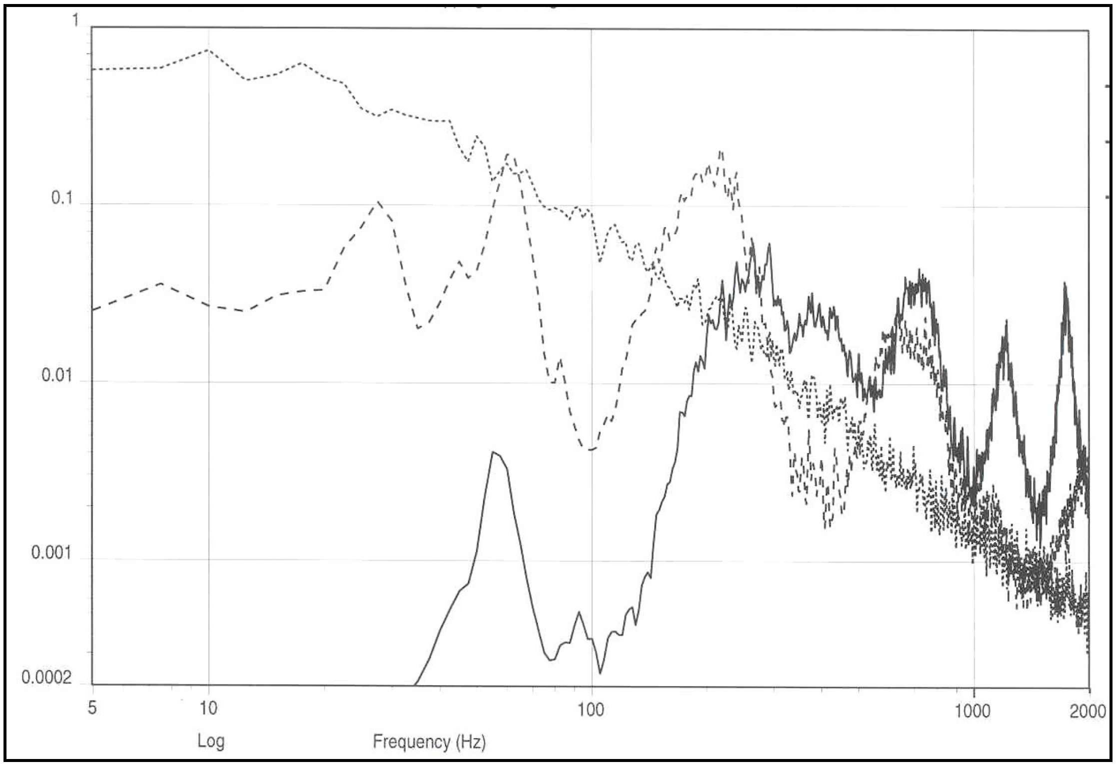


Figure 3.28. SPD measured on the pendulum surface

The SPD response resembled a high pass filter response. Below the natural resonance frequency, the shock and vibration spectrum was attenuated at the rate of 20 dB per decade. This occurred because the dynamics of the pendulum were fast enough to follow and suppress the cutter drum SPD. The frequency domain response of the electronics package is shown in Figure 3.29.

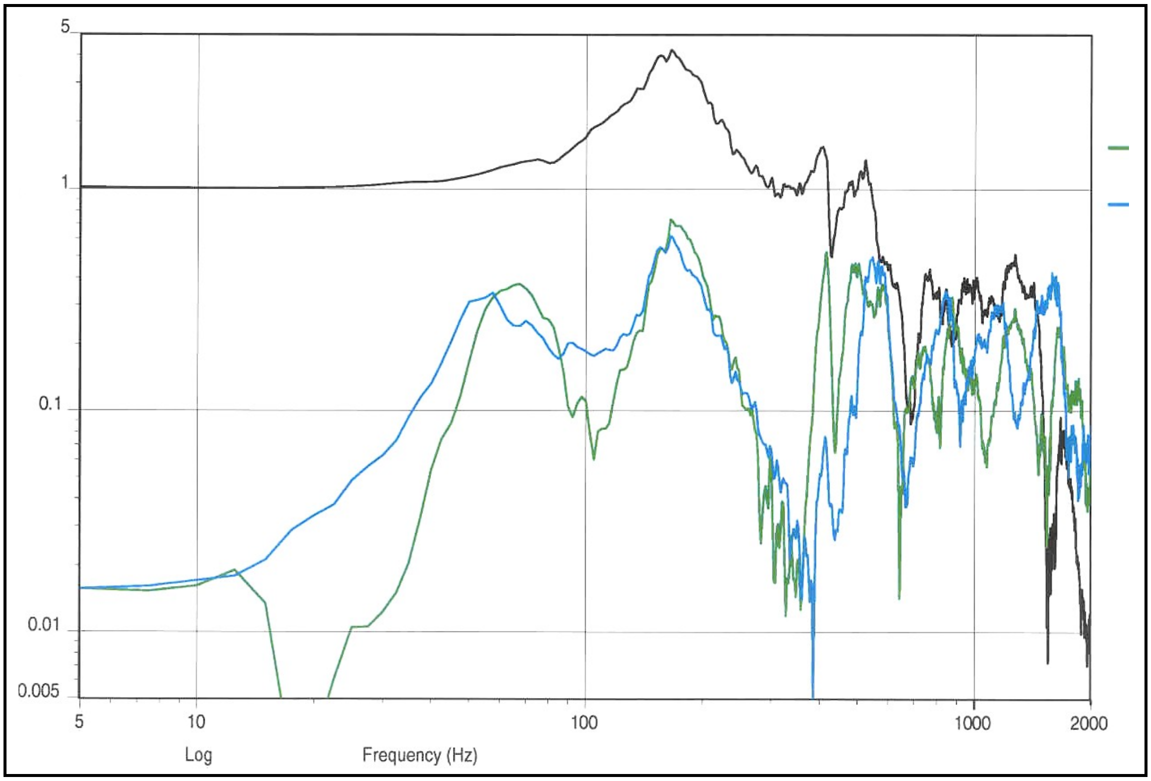


Figure 3.29. SPD of the electronics package (Line color code: black- input direction; green – horizontal normal to input; blue – vertical normal to input).

The natural resonant frequency was near 200 Hz. The vibration dampeners associated with the mechanical design provide attenuation against the cutter drum SPD.

The electric power generation assembly was then endurance-tested by subjecting the unit to 80 hours of tests without failure. The electronics package made sensor impedance measurements during the shock-and-vibration tests. The data were not affected by the cutter drum SPD. The electronics package survived the endurance test.

The conclusion drawn following the endurance testing was that the HS-3 generator and sensor designs passed the endurance tests. Sandia's structure analysis and test center provided insight into the shock and vibration design requirements for the Horizon Sensor. The information gained in the tests enabled the Stolar design team to determine the operating life of the design. The data were also used in the quality assurance program during the production of the product.

3.5.3 *Advanced Shock and Vibration Analysis*

To ensure that the mechanical design specifications of the HS-3 would be sufficient for the cutting profile of standard continuous miners, additional shock-and-vibration analysis was performed midway through the HS-3 development schedule.

On January 17, 2002, an environmental data logger was installed on the surface of a continuous mining machine during production coal mining at the Monterey Coal Company (MCC) No. 1 mine near Carlinville, Illinois. The mining machine was a Joy Model 12CM12-10A. While developing entries, the data logger was installed on the surface of the cutter-drum head and programmed to record the highest magnitude impact and vibration data on a continuous cycle while cutting both coal and rock. While installed, the logger recorded events triggered during the extraction of 24 feet of entry. The entry was 16 feet wide and 7.5 feet high. This mine height included 0.5 feet of rock from the roof. The data logger used was an IST Model EDR3-Turbo. The EDR3T is a self-contained multi-channel shock and vibration recorder with an onboard triaxial accelerometer package, 4 Mbytes of memory, and a variable bandwidth based on setup parameters. Physical and operation parameters are given in Table 3.2.

Table 3.2. EDR3T Characteristics

Size	4.25 x 4.5 x 2.25
Weight	2.2 lbs
Operating voltage	6 VDC (4 C-cell)
Dynamic range	54 dB
Frequency response	0.1 - 1500Hz
Sample Rate	4800 Hz
Trigger level	4.168 g
Transducer Sensitivity	5 mv/g
Maximum event storage	400 events

The EDR3T was mounted within an HSU3002 sensor enclosure, which was mounted on the surface of the left-hand cutter drum, between the cutter's bit blocks. The HS-3 sensor module, power cable, and vibration-dampening springs were removed so that the EDR3T could be mounted on an adapter plate and bolted within the Horizon Sensor Unit (HSU) enclosure. The orientation of the EDR3T recorder was noted for correlation to the drum's rotational coordinated during post-processing. The orientation of the recorder relative to the cutter drum is shown in Figure 3.30. The rotational speed of the drum is 60 revolutions per minute and the EDR3T recorder was mounted at a radius of 17 inches from the center of rotation. The subsequent nominal acceleration of the recorder due to centrifugal force is a straightforward calculation.

Once the EDR3T was installed within the enclosure, the lens assembly was affixed and the miner moved into production. During the next 1.5 hours of production, the EDR3T recorded the 400 highest impact events inflicted on the sensor enclosure during the operation of the miner. While the miner was being moved to an adjacent entry, the recorder was removed and the HS-3 sensor was reinstalled. The recorded data were then downloaded to a laptop computer for analysis.

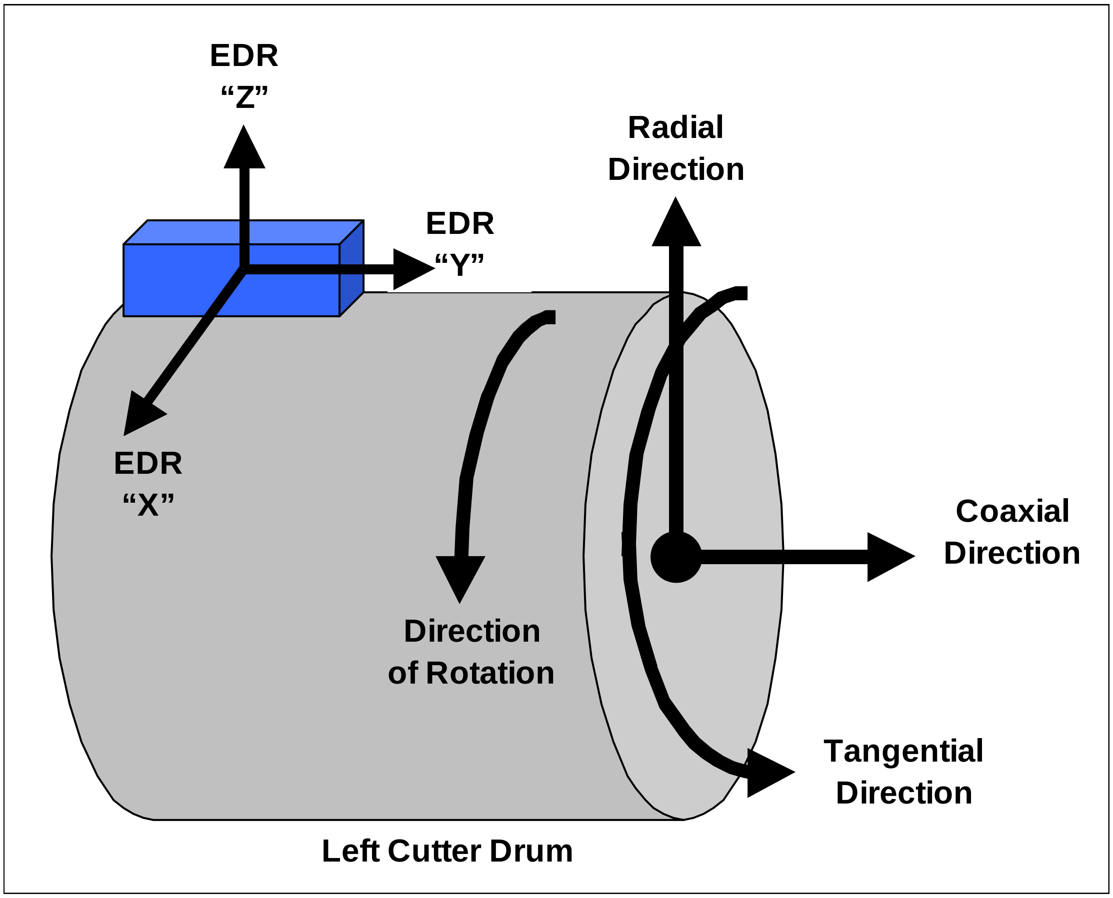


Figure 3.30. EDR3T recorder's axial orientation relative to the cutter drum and its rotational coordinates

The data gathering procedure was as follows:

- Set up the operational parameters of logger. This process consisted of choosing the recording control parameters (RCP) to use for the test. After some initial experience with the EDR3T, and some trial run-throughs during tests at Sandia, the RCPs best used for this setup were determined and the RCP files were created prior to MCC test.

- Set up the EDR3 T using a laptop computer. To set the RCPs, a Windows NT computer was used loaded with Dynamax Suite software and a properly configured RS232 port. The communications and setup module EDR3CCOM was used to interface with the recorder.

- Package and install the EDR3T recorder. The recorder was mounted within the HSU3002 sensor module enclosure and the enclosure was sealed.

- Initiate triggered responses during mining conditions. Coal was cut with the mining machine in its normal usage conditions until an inactive period allowed the recorder to be removed. The impact events were recorded in on overwrite mode, which preserved the 400 highest events in memory during the triggering phase.

- Upload and analyze the data. The EDR3CCOM was used to upload the data via the serial link to the laptop. Once uploaded, it was available for analysis and data processing through the Dynamax Software. Processing included post-processing filters, statistical reports, and the generation of Fast Fourier Transform (FFT) power spectral densities.

The downloaded data were immediately reviewed in a temporal format. This format showed the impact acceleration of all 400 events versus recording time. Included in these events were impacts at all frequencies between 1 and 2500 Hz. The raw data are shown for all three axial components in Figure 3.31. The blue plot is the drum's tangential direction (X component), the red plot is the drum's coaxial direction (Y component), and the green plot is the drum's radial direction (Z component).

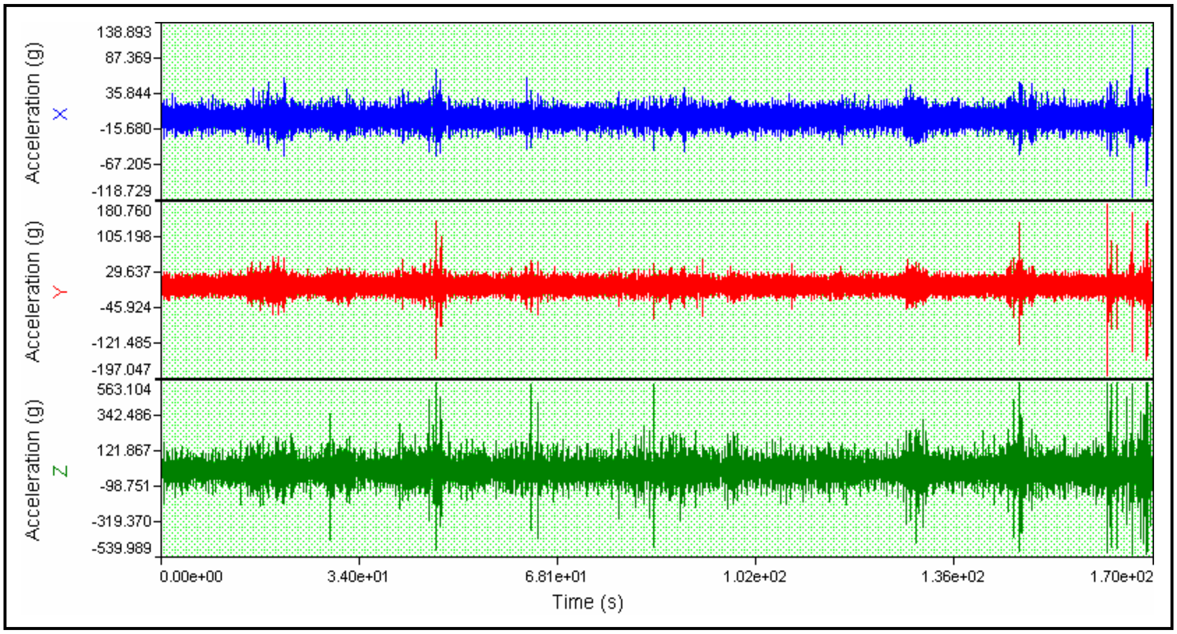


Figure 3.31. Temporal plot of peak acceleration (units of g) in the three axes of the MCC tests

Statistical evaluation of the recorded events can be done to break down the average accelerations seen in the event plots. These values are given in Table 3.3. The number of events within specific g-level groups for each component can also be extracted from the data set.

Table 3.3. Statistical variation of impact events versus axial direction

	Peak Acceleration (g)			RMS Acceleration (g)		
	X (tangent)	Y (coaxial)	Z (radial)	X (tangent)	Y (coaxial)	Z (radial)
Average	4.237	2.358	33.682	4.986	6.553	26.954
St. Deviation	29.432	39.049	186.319	6.981	9.061	14.153
Maximum	133.038	172.594	538.035	26.896	122.372	111.875
Minimun	-97.289	-188.46	-458.04	-116.433	-119.433	-169.207

Given the position of the cutter drum's bit picks, and the nature of the cutting process, the magnitude of the events relative to one another is immediately logical, i.e., the radial component is the highest magnitude, followed by the tangential, and the coaxial is minimal.

The total groups of events are shown in Figure 3.32 in terms of g-force versus component. The blue circles are events in the drum's tangential direction (X component), the red circles are coaxial direction (Y component), and the green circles are radial direction (Z component). Figure 3.32 showed that the majority of the high-level acceleration events were seen in the radial direction of the cutter drum. These events were five times the magnitude of events seen in the other components. In addition, there is a slight but obvious dominance of coaxial events over tangential. It must be kept in mind, however, that this relationship is a generality for ALL frequencies imparted to the recorder during testing.

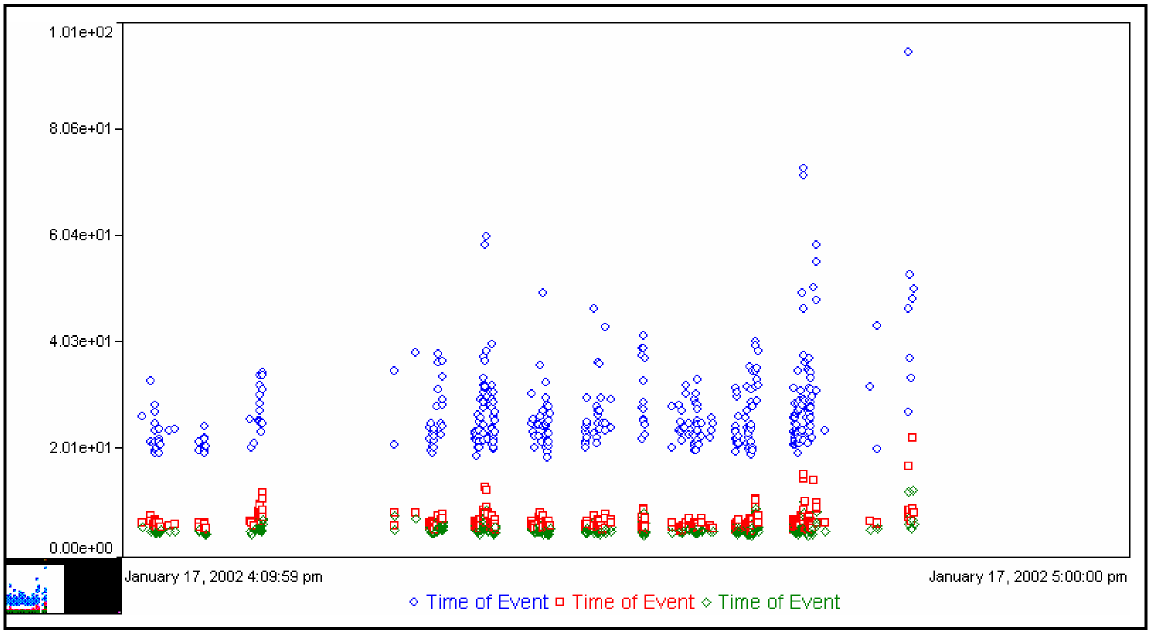


Figure 3.32. Temporal and axial distribution plot of peak acceleration (units of g)

To better understand the distribution of energy in the recorded events, the temporal data were used to generate the PSD behavior or impact events. This PSD illuminated the actual frequencies of the impulses imparted to the recorder during the mining operation, and more importantly, the amount of acceleration energy at a particular frequency. This information was critical in the design specifications of the Horizon Sensor's mechanical parts and helped in the tuning of shock and vibration isolation systems. These systems were composed of spring-steel coil dampeners, rubber bumper pads, and PVC isolation grommets—all of which attenuated vibrational energy, lessening its effect on the system and ensuring resonant failure never occurred.

The PSD plots are shown for all three components in Figure 3.33. These PSD plots were created using a FFT on the data with rectangular spectral windowing and a zero correction pad. The data also had the event mean removed. This mean event energy is most commonly associated with vibration of the recorder package to its mounting plate and was routinely filtered.

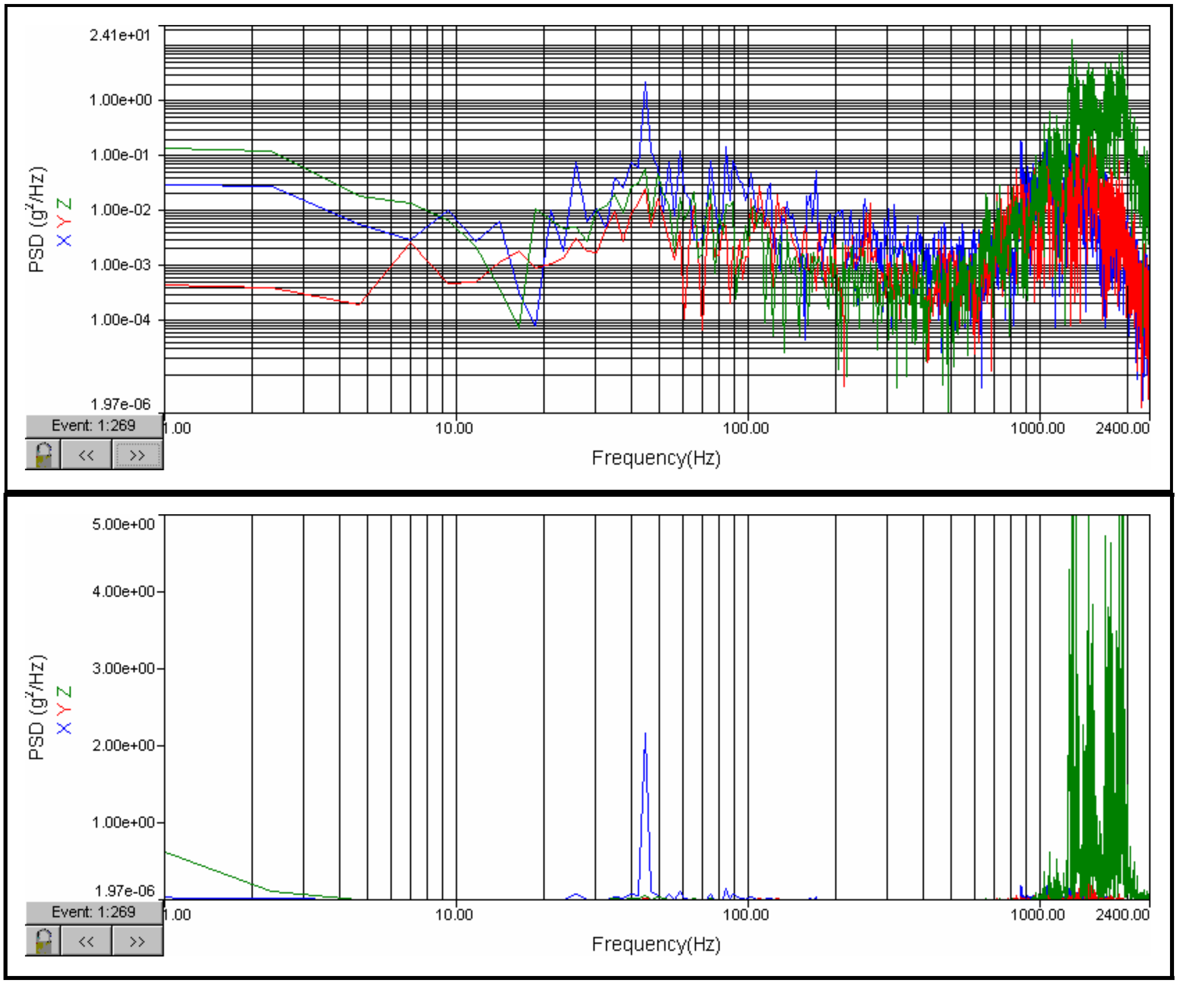


Figure 3.33. Power spectral density of the MCC test data in all three directions; Log 10 and linear scales (top and bottom, respectively)

The acceleration magnitudes of the raw events measured at MCC were greater than those measured on the 14CM15 during similar tests at Enlow Fork. While it could be said that the Monterey coal seam and/or rock was "harder" than the CONSOL material, the real reason for the magnitude increase is the placement of the recording device on the cutter drum's surface, as opposed to its center of rotation. The accelerations at MCC seem to be as high as 100g (root mean square [RMS]), as opposed to 80g recorded at CONSOL.

The relative magnitudes of the three different components were comparatively similar between the 14cm and the 12CM, i.e., the radial component appears the strongest, and the coaxial component the weakest. Further investigation of the data using PSD analysis and frequency dependence yields another story. The extremely high g-force accelerations were found to be at frequencies higher than 1000 Hz, while the frequency band between 1 and 1000 Hz had very little energy beyond peaks seen near 40 to 50 Hz. Even at these frequencies, the acceleration values were low (less then 10g) compared with the 100g seen in the temporal data plots.

This behavior had become typical of vibrational analysis done during the course of the HS program. The lower frequency impulses had relatively high displacements and low g-force, while all the apparent acceleration occurred in extremely low-displacement events in the upper frequency band.

The PSD plots showed that the majority of the mining machine's destructive impact energy resided between 40 and 50 Hz and resulted from the impact of the cutter picks on the coal rib. The less destructive vibrational energy occurred above 1000 Hz and resulted from component vibration and mechanical oscillation of moving parts and motors as well as the abrasion of material along the cutter's moving parts.

These conclusions imply that the Horizon Sensor's vibrational dampening system was more then adequate to deal with the mining conditions encountered on miners in similar cutting regimes. The system attenuated energy in the proper frequency band (above 300 Hz), and did not amplify energy in the machine's operating frequency band (below 100 Hz).

The pretuned natural mechanical frequencies of the HS modules were thus purposely tuned to be within an intermediate band (100 to 300 Hz) where the mining machine exhibited no significant vibrational energy of acceleration.

The consequences of these measured and analyzed data sets great impacted the design, form, and function of the commercial HS-3 Horizon Sensor.

4. Experimental – HS Product Line Development

4.1 Horizon Sensor (HS-3) Product Line

A product line of Horizon Sensor systems for different applications was developed throughout 2001 and 2002. This product line consisted of the following systems (and machine types):

- HS-CM: Horizon Sensor for Continuous Miners
    - HS-CM/P: With internal power generator
    - HS-CM/B: With on-board battery pack
- HS-LW: Horizon Sensor for Longwall (LW) Shearers
    - HS-LW/P: With internal power generator
    - HS-LW/B: With on-board battery pack
- HS-BM: Horizon Sensor for Bore Miners (BM)
    - HS-BM/P: With internal power generator
    - HS-BM/B: With on-board battery pack
- HS-HW: Horizon Sensor for Bore Miners
    - HS-BM/P: With internal power generator
    - HS-BM/B: With on-board battery pack
- HS-SE: Horizon Sensor for Surface Excavation Equipment
- HS-P: Portable Hand-Held Horizon Sensor

Note: When HP is used exclusively with no sensor module, an HP term replaces the HS in the product code. For example, an HP-CM is a continuous mining machine with head-positioning functionality only (Current and Total Mining Height).

4.2 Horizon Sensor Engineering and Manufacturing

Stolar has manufacturing capability in addition to its engineering groups. In its 12,000-square-foot production area, Stolar manufactures the primary electronic components for its HS products, along with the majority of its mechanical parts and related subassemblies. Final assembly of all HS products is done at the Raton facility. Stolar can expand manufacturing capacity in Raton.

Stolar has developed special skill for electronic manufacturing and testing of its HS products, which provides us with a high level of quality control and reliability. Our manufacturing processes are in compliance with IPC standards, and Stolar is in the process of qualifying for ISO 9001 and ISO 9002 certifications. Figures 4.1 and 4.2 show several HS production tasks being performed at the Stolar facility.

Figure 4.1. Horizon Sensor production facility including: circuit board assembly (lower left), circuit board testing(upper left), sensor module assembly (upper right), and generator module assembly (lower right)

With the exception of early underground system testing, all levels of the Horizon Sensor development were done at Stolar's laboratory in Raton, New Mexico. As the commercial version of the Horizon Sensor system (HS-3) began to reach its final stages of development, more resources were put into expanding Stolar's production and quality control facilities. A machine shop and manufacturing area were created to handle the fabrication and testing duties associated with the new HS product line.

The quality assurance programs in place at the HS production facility include:

- Electrical performance testing of submodules
- Certification compliance testing of X/P enclosures
- Thermal and environmental testing of assembled modules

- Vibration and impact testing of damped mechanical chassis
- Complete system simulation for continuous miner, longwall shearer, and bore miner applications

Figure 4.2. Horizon Sensor production facility including: RF-circuit tuning (lower left), chassis and wire harness assembly (upper left), display module assembly (upper right), and electronics thermal testing(lower right)

Figure 4.3 shows an HS-CM system being tested prior to shipment. The tests shown include vibrational dampening control on a shaker table as well as final quality assurance testing on the CM simulator.

Figure 4.3. Testing of a commercial HS-CM system including vibration (top) and miner simulation (bottom)

4.3 Horizon Sensor System Modules

The Horizon Sensor Product Line is entirely manufactured by Stolar (unless noted otherwise) and consists of specifically coordinated combinations of the following modules (model number and model name):

- HSU-3001: Drum-Mounted Horizon Sensor Unit for Short Bit Block Drums
- HSU-3002: Drum-Mounted Horizon Sensor Unit for Tall Bit Block Drums
- HPU-3001: Drum-Mounted Horizon Power Generation Unit
- HBU-3001: Drum-Mounted Horizon Battery Unit
- HGU-3001: Operator Accessible Horizon Graphics Unit (side exiting glands)
- HGU-3002: Operator Accessible Horizon Graphics Unit (bottom exiting glands)
- HGU-3003: Operator Accessible Horizon Graphics Unit (rear exiting glands)
- MA001041-0014: Cutter Boom Inclinometer (CBI) (Joy Mfg)
- CBI-3001: Cutter Boom Inclinometer
- A800275: GUI Power Input Board Assembly
- A000000: GUI Modem Arial Assembly
- PSH-001: Portable Sensor Head
- PGH-001: Portable Graphics Head
- PBP-001: Portable Battery Pack
- HHC-001: Portable Hand-Held Chassis Assembly
- HGR: Horizon Graphics Remote

4.3.1 HSU Sensor Module

The HSU sensor unit radiates RF energy into the coal seam and measures backscattered signal levels that are proportional to uncut coal thickness. These signal levels are the basis of a measurement technique that provides the miner operator with a thickness estimate. This sensor, with protective cover, will be mounted within the surface of the cutter drum in a flameproof enclosure, but below the bit block circle. The HSU is shown in Figure 4.4.

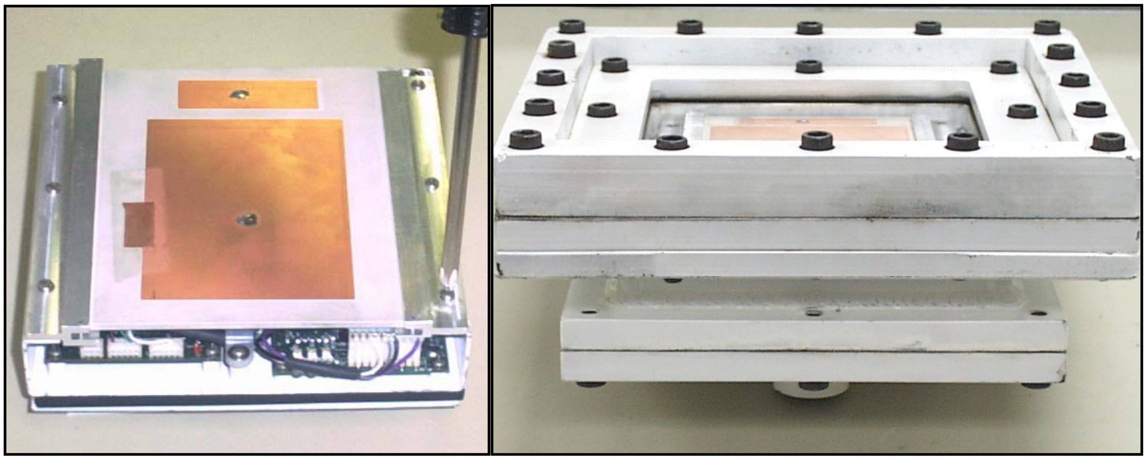


Figure 4.4. HSU electronics chassis and enclosure

There are two types of HSU enclosure, one for cutter drums with tall (greater than 6 inches [152mm]) bit blocks, and one for drums with short blocks (less than or equal to 6 inches [152mm]). These are the HSU-3002 and HSU-3001 models, respectively.

HSU-3001 Through-Hole Model (TH)

HSU definition:	Horizon Sensor Unit
Model #:	HSU-3001
Module Name:	HS-3 Horizon Sensor Unit (Model 1)
MSHA Approvals:	X/P-4168-0
Size:	Exposed Section: 11.2" x 11.2" x 1.7" [285mm x 284mm x 43mm]
	Recessed Section: 7.3" x 7.3" x 2.75" [185mm x 185mm x 70mm]
Weight:	65 lbs. [29.5 kg]
Input Power Requirements:	10-30 VAC or VDC (6 Watts)
Input Power Protection:	5-amp fast-blow fuses
Output RF Frequency: Modem:	910–923 MHz – Spread Spectrum
	RMPA: 430 to 520 MHz – Programmable
Output RF Power:	Modem: 100mW to 1W – Programmable
	RMPA: 10mW to 50mW – Variable

Output RF Protection: None (radiates through the lens cover)

Mounting Space Required: 7.5" x 7.5" [185mm x 185mm] square hole through drum and 2.2" x 11.2" x 11.2" [64mm x 285mm x 285mm] surface area on drum

Enclosure Features: Removable upper cover consisting of polycarbonate lens and retainer – removable lower cover with single entry gland.

Circuit Boards: Millennium RF Board

RMPA Antenna and Coupler

R/C Power Board

RF Modem

Acceleration Power Relay Board (on systems with HBU only)

Major Components: Rectangular X/P Enclosure with non-metallic lens

Control Electronics Chassis with RF, RMPA, and Modem

Wire rope spring isolators

Entry Glands: Single (1) packing-box type gland on lower cover

Install Configuration: For drums with bit block height less than 6 inches the HSU-3001 mounts on cutter drum surface, between bit blocks. The body of the HSU enclosure passes though an access hole (7.5" [191mm] square aperture) in the drum. A bolt ring is welded into place around the drum aperture. The HSU-3001 is termed the Through-Hole (TH) design.

Installation Requirements: A clearance hole must be made on through the cutter drum of dimensions 7.5" x 7.5" [191mm x 191mm]. The bolt-ring flange welds to the top of the hole.

HSU-3002 Drop-Box Model (DB)

HSU definition: Horizon Sensor Unit

Model #: HSU-3002

Module Name: HS-3 Horizon Sensor Unit (Model 2)

MSHA Approvals: X/P-4169-0

Size:	Exposed Section: 11.2" x 11.2" x 4.5" [285mm x 284mm x114mm]
Weight:	88 lbs. [40 kg]
Input Power Requirements:	10-30 VAC or VDC (6 Watts)
Input Power Protection:	5-amp fast-blow fuses
Output RF Frequency:	Modem: 910-923 MHz - Spread Spectrum RMPA: 430 to 520 MHz - Programmable
Output RF Power:	Modem: 100mW to 1W – Programmable RMPA: 10mW to 50mW - Variable
Output RF Protection:	None (radiates through the lens cover)
Mounting Space Required:	DB: 2.5" [64mm] diameter hole through drum and 4.5" x 11.2" x 11.2" [114mm x 285mm x 285mm] surface area on drum OD
Enclosure Features:	Removable upper cover consisting of polycarbonate lens and retainer and a solid welded bottom plate with single entry gland.
Circuit Boards:	Millennium RF Board RMPA Antenna and Coupler R/C Power Board RF Modem Acceleration Power Relay Board (on systems with HBU only)
Major Components:	Rectangular X/P Enclosure with non-metallic lens Control Electronics Chassis with RF, RMPA and Modem Wire rope spring isolators
Entry Glands:	Single (1) packing-box type gland on lower plate
Install Configuration:	For drums with bit block height greater than 6" [152mm], the HSU-3002 mounts on cutter-drum surface, between bit blocks. The body of the HSU enclosure drops into a

	surface-mounted bolt ring box. Only a 2.5" [64mm] hole is cut into the drum shell to allow passage of the entry gland into the drum. The HSU3002 is termed the Drop-Box (DB) design.
Installation Requirements:	A 2.5" [64mm] diameter hole must be made through the drum for entry gland clearance and an 11.2" x 11.2" [285mm x 285mm] surface area is required on the drum OD for the Drop-box.

4.3.2 HPU Power Generator Module

The operating voltage for the HSU system will originate from the HPU by means of an electrodynamic generator in an MSHA-approved flameproof enclosure, or from a battery pack within a flameproof enclosure. The HPU is shown in Figure 4.5.

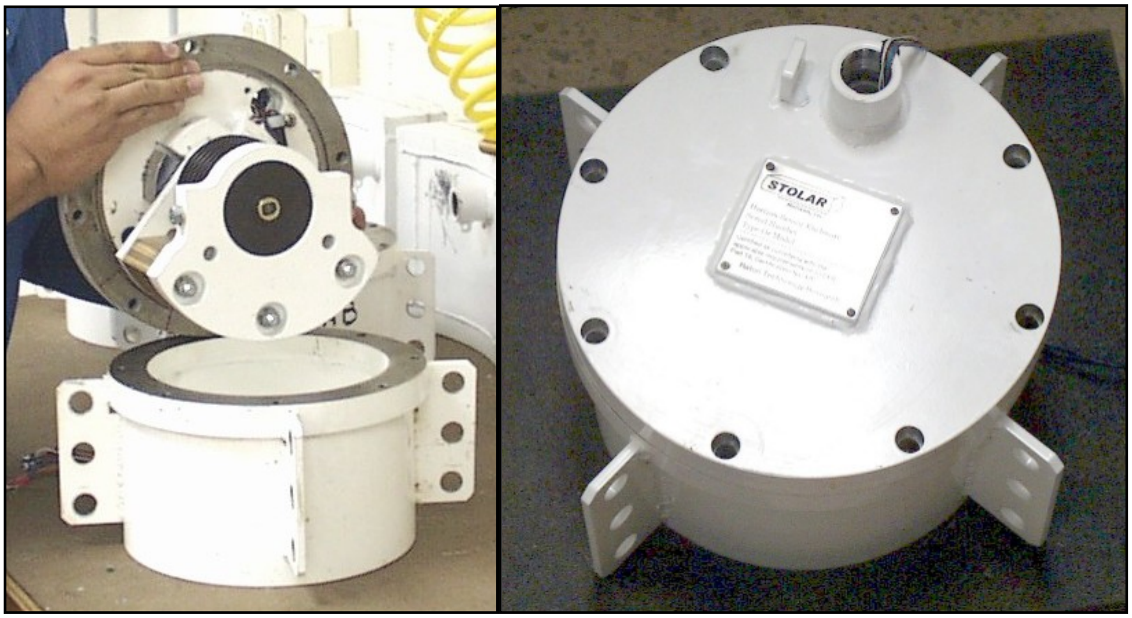


Figure 4.5. HPU generator system and X/P enclosure

HPU definition:	Horizon Power Unit
Model #:	HPU3001
Module name:	HS-3 Horizon Power Generator Unit (Model 1)
MSHA Approvals:	X/P-4163-0
Size:	Enclosure Section: 9.5" [242mm] diameter, 6.85" [174mm] depth enclosure with mounting brackets and entry gland: 13.5" [343mm] diameter, 10.5" [167mm] depth

Weight:	65 lbs. [30 kg]
Output power:	18-24 VAC 3-phase (at 50 - 70 RPM)
Output power protection:	three 5-amp fast-blow fuses (one per phase)
Enclosure features:	Outer steel cover, four radial mounting tabs on OD of cylindrical enclosure.
Circuit boards:	AC Voltage Generator Fuse Board - three @ 5A
Major Components:	Cylindrical X/P Enclosure with radial mounting brackets Power generator with weight assembly Rubber Grommet Isolators
Entry Glands:	Single packing-box type gland on cover
Install Configuration:	Cutter drum cavity at center of rotation
Installation Requirements:	Weld on mounting brackets within drum cavity. Minimum cavity dimensions required: 13.5" [343mm] Diameter, 13" [330mm] Depth; Drum must have rotation speed of 45–75 RPM

4.3.3 HBU Battery Module

The operating voltage for the HSU system can also originate from the HBU by means of a battery pack within a MSHA-approved flameproof enclosure. This battery module is attached to the surface of the cutter drum, near the HSU, and is used on those machines that lack the internal cavity space required for the HPU generator. The HBU is shown in Figure 4.6.

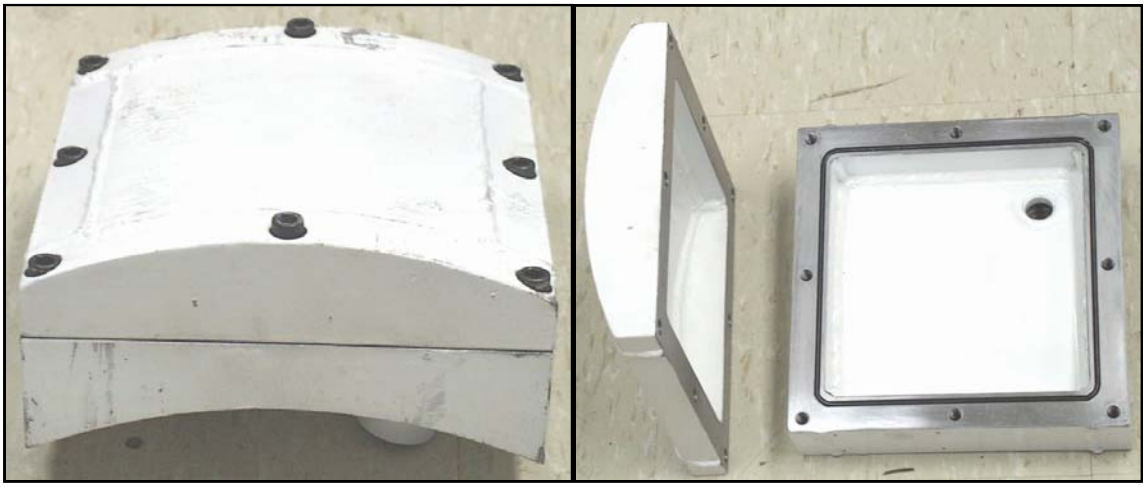


Figure 4.6. HBU battery X/P enclosure

HBU definition:	Horizon Battery Unit
Model #:	HBU3001
Module name:	HS-3 Horizon Battery Unit (Model 1)
MSHA Approvals:	X/P-4173-0
Size:	Enclosure Section: 9" x 9" x 2.5" [229mm x 229mm x 64mm] with 10.5" [267mm]-radius curvature
Weight:	45 lbs. [21 kg]
Output power:	18-24 VAC 3-phase (at 50–70 RPM)
Output power protection:	three 5-amp fast-blow fuses (one per phase)
Enclosure features:	Upper steel cover and lower steel cover with entry gland
Circuit boards:	Trigger switch assembly
	5-amp inline fuse
Major Components:	Square X/P Enclosure
	Solid Lithium Battery Pack
	Foam padding
Entry Glands:	Single packing-box type gland on lower plate
Install Configuration:	Cutter-drum surface between bit picks

Installation Requirements:	Lower plate welds onto drum, upper plate bolts to lower plate. Single 2.5" [64mm] hole cut into drum for entry gland clearance.

4.3.4 HGU Graphics Display Module

The HGU graphics display module receives and processes measurement data from the HSU sensor module. Its internal electronics are collectively referred to as the GUI. The HGU is used to control and calibrate the system and its variables of operation by means of a central processing computer and push button menu scheme. The HGU is shown in Figure 4.7.

Figure 4.7. HGU graphics display electronics and X/P enclosure

HGU Definition:	Horizon Graphics Unit
Model #:	HGU-3001
Module Name:	HS-3 Horizon Graphics Unit (Model 1)
MSHA Approvals:	X/P-4167-0
Size:	Enclosure Section: 9.3" x 8.7" x 5.9" [236mm x 221mm x 150mm] enclosure with mounting brackets, entry glands, and plunger switches: 10.5" x 11" x 5.9" [267mm x 280mm x 150mm]
Weight:	57 lbs. [26 kg]
Input Power Requirements:	10-30 VDC (6 Watts)
Input Power Protection:	5-amp fast-blow fuse
Output RF Frequency:	910-923 MHz: Spread Spectrum

Output RF Power:	100mW to 1: Programmable
Output RF Protection:	3-capacitor DC barrier block (0.3 microfarad)
Output inclinometer voltage:	12 VDC
Output voltage protection:	1-amp fast-blow fuse
Mounting Space Required:	No limitations
Enclosure Features:	Upper cover consisting of polycarbonate lens and retainer, dual mounting tabs on top and bottom of enclosure.
Circuit Boards:	Color graphic display: 4.2" x 6" [106mm x 152mm] Microcomputer Module I/O Board Power Distribution Module RF Modem Module
Major Components:	Rectangular X/P Enclosure with non-metallic lens Display Electronics Chassis with Modem Side-mounted Plunger Switches Wire rope spring isolators
Entry Glands:	Four packing-box type glands on enclosure walls Four side-entry glands (Model # HGU-3001) Four bottom-entry glands (Model # HGU-3002), Four back-entry glands (Model # HGU-3003) Four plunger switches
Install Configuration:	Rear of miner near control box power – can mount on vertical or horizontal surface, mounting brackets adaptable on horizontal or vertical surface of 11" x 11" (280mm x 280mm).
Installation Requirements:	HGU requires GUI Power Input Module to be installed in Miner control box and cable routed through gland to HGU.

4.3.5 Cutter Boom Inclinometer

The cutter boom inclinometer (CBI) is mounted on the side of the boom itself (internally) and measures the angle of the boom relative to the body of the miner. This angle is used in the processing of HSU data, providing mine height and drum position coordinates. The Horizon Sensor system can use one of two CBI types: one is of Stolar design (Model # CBI-3001) and one is a Joy Mining part (Model# MA001041-0014). The Stolar unit is the smaller of the two and is the preferred inclinometer. The CBI is shown in Figure 4.8.

Figure 4.8. CBI module and X/P enclosure

CBI:	Cutter Boom Inclinometer
Model #:	CBI-3001 or Joy Model# 603142-2
Module name:	HS-3 Cutter Boom Inclinometer (Model 1)
MSHA Approvals:	Stolar Model# CBI-3001: X/P-4175-0
Size:	Enclosure only 5" x 5" x 4" [127mm x 127mm x 102mm]; total with mounting tabs and gland 4" x 7" x 8" [102mm x 178mm x 203mm]
Weight:	12 lbs [5.5 kg]
Input power:	12 VDC (0.25A continuous draw)
Input power protection:	1-amp fast-blow fuses
Output power:	±16 VDC (0.02A continuous draw)
Output power protection:	0.125-amp polyswitch
Enclosure features:	Top steel cover, two mounting tabs on lower sides of enclosure

Circuit boards:	Stolar Model# CBI-3001: #DAS-30 Inclinometer controller
Major Components:	Cubical X/P enclosure with mounting brackets
Entry Glands:	Single packing-box type gland in side wall
Install Configuration:	Inclinometer must be mounted internal to cutter boom arm or on the side of cutter boom if well protected. Mounting Brackets adaptable to horizontal or vertical surfaces of 5" x 7" (280mm x 280mm) area. Brackets are affixed to welded thread-bosses for mounting tabs.

4.3.6 HGU Peripherals – GUI Power Input Board

The GUI Power Input Board (GPIB) is required to regulate and filter the power originating from the mining machine and consumed by the GUI within the HGU. The PIB is mounted within the control box enclosure of the mining machine. The GPIB is shown in Figure 4.9.

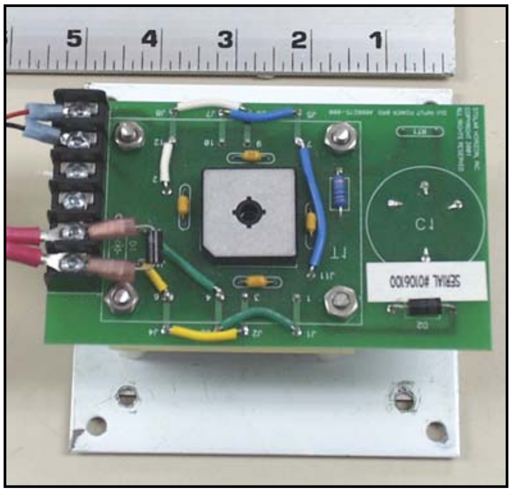


Figure 4.9. GUI Power Input Board

PIB definition:	GUI Power Input Board
Model #:	A800275-000
Module name:	HS-3 GUI Power Input Board (Model 1)
MSHA Approvals:	None
Size:	5" x 5" x 3" [127mm x 127mm x 76mm]
Weight:	3 lbs [1.4 kg]
Input power:	90–240 VAC (0.25A continuous draw)

Input power protection:	MOV-Resistor Bridge
Output power:	18–24 VDC (1.2A continuous draw)
Output power protection:	3-amp polyswitch
Circuit boards:	Power input board. AC/DC Rectifier DC Fuse (5A Polyswitch)
Major Components:	Mounting plate Terminal wire harness strip 120/24 VAC Transformer DC Filtering Capacitor
Entry Glands:	Installation of PIB requires a single spare gland in side wall of the miner’s control box.
Install Configuration:	Mounting plate is 5" x 5" and can be drilled to any bolt pattern available in the control box.

4.3.7 HGU Peripherals – GUI Modem Aerial

The GUI Modem Aerial (GMA) is required to provide modem communications between the HSU on the cutter head and the HGU viewed by the miner operator. The GMA is an assembly consisting of an I.S. antenna cable and a protective housing. The cable originates from the HGU enclosure and is routed to the housing through protective rubber conduit. The aerial housing is composed of a steel base plate (weld plate), an antenna mount plate, and a nylon antenna cover. The GMA can be located anywhere on the miner provided radio reception between it and the HSU is high quality. The GMA is shown in Figure 4.10.

Figure 4.10. GUI Modem Aerial and I.S.-approved DC Barrier Block

GMA definition: GUI Modem Aerial

Model #:	GMA-3001
Module name:	HS-3 GUI Modem Aerial Antenna Assembly (Model 1)
MSHA Approvals:	Intrinsically Safe antenna cable assembly and DC-barrier block assembly I.S. # 1A-21110-0
Size:	5" x 5" x 3" [127mm x 127mm x 76mm]
Weight:	10 lbs [1.4 kg]
Output RF Frequency:	910–923 MHz: Spread Spectrum
Output RF Power:	100mW to 1: Programmable
Output RF Protection:	3-capacitor I.S. DC-barrier (3 x 0.47 microfarad capacitance)
Circuit boards:	DC-barrier block board
Major Components:	DC-barrier block assembly Semi-rigid copper/brass coax adapter for entry gland Primary coaxial cable Whip antenna Aerial housing (base plate, antenna mount plate, antenna cover)

Entry Glands:	The aerial housing is mounted on the body of the mining machine and is connected to the GUI modem through the DC-barrier block. The block is located inside the HGU enclosure and the aerial antenna is routed through one of the HGU entry glands.
Install Configuration:	The lower base plate of the GMA housing must be welded to the mining machine. This should be done near the top of the machine or in a location with general line-of-sight to the cutter drum and HSU sensor. The antenna mount plate bolts to the welded base plate and supports the whip antenna. The whip antenna is then capped and sealed with the nylon cover.

4.3.8 HGU Peripherals – Horizon Graphics Remote

The Horizon Graphics Remote (HGR) allows surface operation of the HGU through a serial umbilical cable. It is used to control and calibrate the system and its variables of operation by means of a central processing computer and pushbutton menu scheme. The HGR is shown in Figure 4.11.

Figure 4.11. HGR submodule with LCD display, key-pad, and aluminum enclosure

HGR definition:	Horizon Graphics Remote
Model #:	HGR-3001
Module name:	HS-3 Horizon Graphics Remote (Model 1)
Circuit Boards:	Color graphic display: 4.2" x 6" (106mm x 152mm) Microcomputer Module

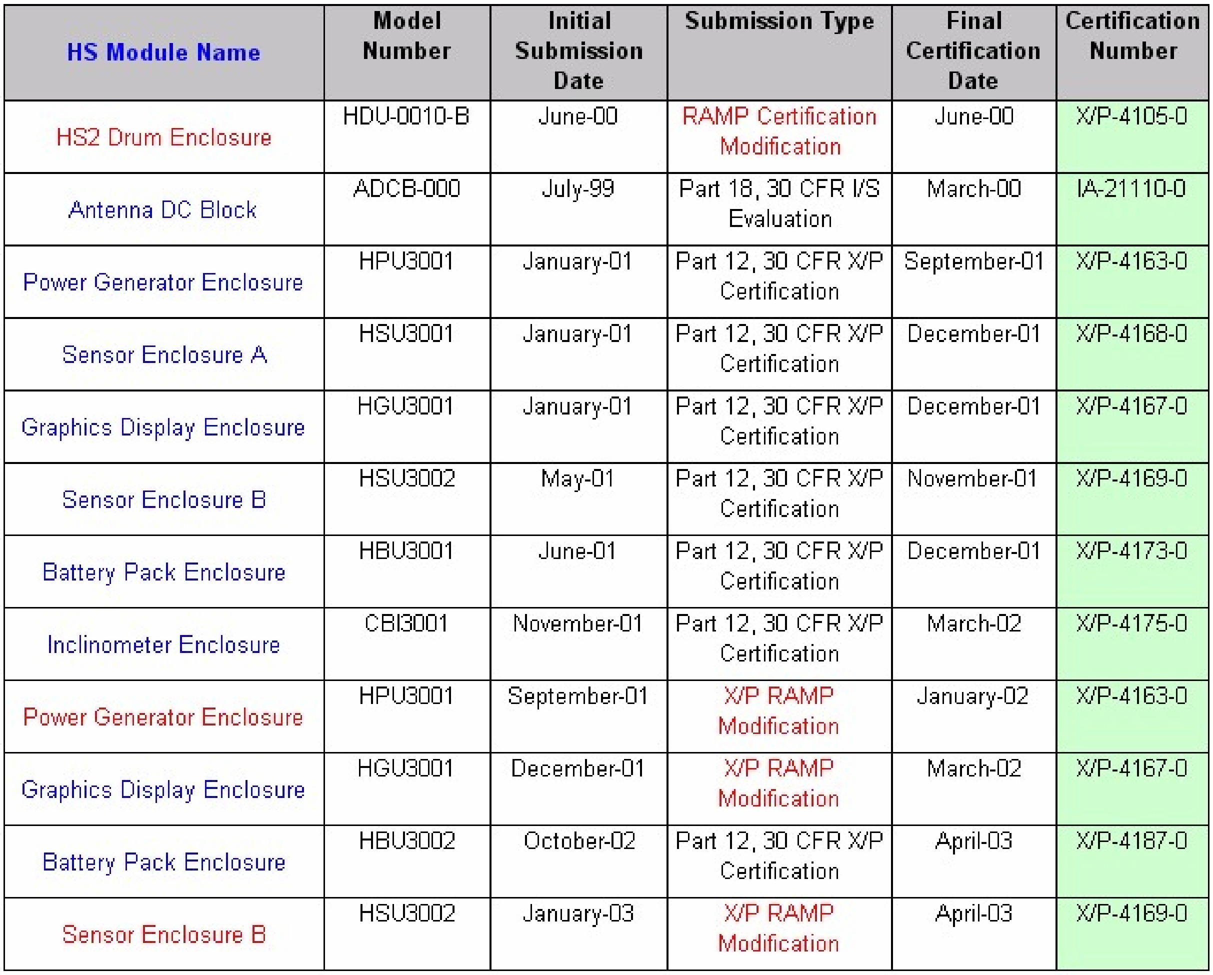
	Power Distribution Module
Major Components:	Rectangular non-X/P Enclosure
	Display Electronics Chassis
	Pushbutton Key Board
Size:	Enclosure Section: 10" x 8" x 4" (254mm x 203mm x 102mm)
Weight:	12 lbs. (5.5 kg)
Input Power Requirements:	12–24 VDC (6 Watts) or 110-130 VAC
Installation Requirements:	Mounting Brackets adaptable on horizontal or vertical surface of 10" x 8" (254mm x 203mm).
NOTE:	HGU requires GUI Power Input Module to be installed in Miner control box and cable routed through gland to HGU.

4.4 Horizon Sensor MSHA Certifications

Each module in the HS product line has MSHA certifications that were acquired over the course of the product line's development. The module enclosures all have X/P certifications and the antenna assemblies each have an I.S. certification. These MSHA approvals began to be submitted and accepted as early as 1998 when the HS-1 program was in operation. The HS-2 system required modifications to the original approvals. However, the ramp up to the HS-3 system development required the design and certification of many new components.

This approval process continued for nearly the entire duration of the HS-3 program, as new subsystems were developed that affected the form, function, and volume of their approved enclosures. Certifications were always coordinated by Stolar Engineers and a single approval could take anywhere from 3 months to 2 years depending on the scope, complexity, and number of design iterations required. Table 4.1 shows the type and number of HS certifications acquired during the DOE-funded HS development cycle.

Table 4.1. Certification acquired over the HS program (2000-2003)



HS Module Name	**Model Number**	**Initial Submission Date**	**Submission Type**	**Final Certification Date**	**Certification Number**
HS2 Drum Enclosure	HDU-0010-B	June-00	RAMP Certification Modification	June-00	X/P-4105-0
Antenna DC Block	ADCB-000	July-99	Part 18, 30 CFR I/S Evaluation	March-00	IA-21110-0
Power Generator Enclosure	HPU3001	January-01	Part 12, 30 CFR X/P Certification	September-01	X/P-4163-0
Sensor Enclosure A	HSU3001	January-01	Part 12, 30 CFR X/P Certification	December-01	X/P-4168-0
Graphics Display Enclosure	HGU3001	January-01	Part 12, 30 CFR X/P Certification	December-01	X/P-4167-0
Sensor Enclosure B	HSU3002	May-01	Part 12, 30 CFR X/P Certification	November-01	X/P-4169-0
Battery Pack Enclosure	HBU3001	June-01	Part 12, 30 CFR X/P Certification	December-01	X/P-4173-0
Inclinometer Enclosure	CBI3001	November-01	Part 12, 30 CFR X/P Certification	March-02	X/P-4175-0
Power Generator Enclosure	HPU3001	September-01	X/P RAMP Modification	January-02	X/P-4163-0
Graphics Display Enclosure	HGU3001	December-01	X/P RAMP Modification	March-02	X/P-4167-0
Battery Pack Enclosure	HBU3002	October-02	Part 12, 30 CFR X/P Certification	April-03	X/P-4187-0
Sensor Enclosure B	HSU3002	January-03	X/P RAMP Modification	April-03	X/P-4169-0

In addition to MSHA certifications in the United States, the Horizon Sensor modules (I.S. and X/P) were also certified for use in South Africa and Australia. These approvals followed International Standards for electrical apparatuses in explosive gas atmospheres (IEC codes outlined by the International Electrotechnical Commission).

For each HS installation on an underground mining machine, Stolar would also have to work with the mining company and the Original Equipment Manufacturer (OEM) to acquire a complete system approval for the machine itself. Since the mining equipment already has an approval, the addition of the approved HS system requires that the machine approval be modified to include the HS specifications. This process was done using an MSHA program termed Revised Approval Modification Program (RAMP). This RAMP approval would take between 3 and 8 weeks for each customer. Once a RAMP approval was obtained for a specific model of mining machine, the approval process became easier due to having existing systems in operation and a precedent set in MSHA evaluation and documentation. Over the course of the program, RAMP approvals were obtained for Joy continuous miners (14CM-15, 12CM-12, and 12CM-

10A), Voist Apline continuous miners (ABM-14 and ABM-25), Joy longwall shearers (4LS and 7LS), and Marietta Bore Miners.

4.5 Additional Sensor Development

In addition to the Horizon Sensing and head-positioning functions of the HS system, other companion systems were partially developed during the period of DOE program support. These systems include early development and testing of the forward-looking radar (a direct HS subsystem developed by Stolar) and the development of a bit-pick loading sensor (a related HS accessory developed by the Colorado School of Mines).

4.5.1 HS-RADAR Development

Stolar is conducting a demonstration effort termed Horizon Sensor (HS)-Radar to detect voids ahead of coal mining. Stolar has completed the Phase 1 effort, as outlined in the HS-Radar demonstration plan. The results of Phase 1, as explained below, are positive and Stolar will move forward to Phase 2. We provide relevant background information in the next few paragraphs to set the context for our work. The next section discusses relevant technical information about radar, and the test results of Phase 1. The last section of this report documents our conclusions.

The earliest work using a ground-probing radar for exploration of coal, as well as other mining and engineering "rocks," was carried out by John C. Cook of the Teledyne Geotech Corporation in the early 1970s. Cook analyzed samples to determine their probing distance, which is determined primarily by two factors: 1) the material loss, and 2) the dynamic range of the radar. The material loss is the most important factor. When the material loss is high, the improvement in the dynamic range of the radar only slightly increases the probing distance. In general, an increase in the frequency of operation results in a decrease in the probing range. Table 1 reproduces the results of Cook's experiments for coal samples, measured at 100 MHz with a radar whose dynamic range is 100 dB.[1] Cook also showed that in coal, vertically polarized waves (electric field perpendicular to the bedding) resulted in higher losses than horizontally polarized waves (electric field parallel to the bedding). A horizontally polarized antenna, as opposed to a circularly polarized or a vertically polarized antenna, is the appropriate type of antenna for detecting the features of a planar reflector, such as a large void in a coal seam.

Table 4.2. Probing distance (detection range) of a radar with a 100-dB dynamic range for coal exploration at 100 MHz

Location	Probing Distance (ft)
Pittsburg Seam, USA	72
Virginia, USA	66
Colorado, USA	57
Ohio, USA	33
England	23

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[1] Cook, J. C., "Radar transparencies of mine and tunnel rocks," *Geophysics,* vol. 40, No. 5, pp. 865–885, Oct. 1975

Cook used an impulse-radar for his experiments. The impulse radar transmits a short-time EM pulse and its return signal is measured. In the stepped-frequency radar (SFR) approach, which Stolar is employing for reasons stated in Section II, continuous-wave measurements of both magnitude and phase are collected at several frequencies.

Robert L. Chufo of the U.S. Bureau of Mines used an SFR operating over a frequency range of 0.6-1.4 GHz at 2-MHz intervals to measure and characterize the coal and its bounding layer.[2] This method required a servo-controlled antenna positioner to vary the distance between the material and the antenna over a distance of 40 cm in 1.27-cm increments. Moving the antenna during data collection allows the independent measurement of the relative dielectric constant of the coal layer, which is imperative in determining the true thickness of coal. Chufo showed that his technique is accurate to within 5% in measuring coal seam properties. The key to focusing the image of an underground object with any ground-probing radar is multiple antenna placements, or multiple antennas in predefined positions.

Surface-penetrating radar is an extension of the airborne radar whose impetus was World War II. The two main competing technologies for radar are time-domain (impulse) and frequency-domain. The impulse radar system transmits a short burst of EM energy and measures the received signal as it is reflected from a scatterer. The vast majority of the existing radar systems are impulse. A frequency-domain radar measures the phase and the amplitude of a target-reflected signal over a broad frequency band. The advantages of the frequency-domain radar are its wider dynamic range, lower noise figure, higher radiated power, and increased accuracy. The disadvantage of the frequency-domain radar is the increase in data collection time.

The SFR is one of the main subcategories of the frequency-domain radar. In an SFR, data are colleted at several closely spaced frequencies. An SFR may be built around a microwave vector network analyzer (VNA) and as the prices of the VNAs continue to drop, the SFR will be deployed in more radar systems. Over the past decade, Stolar has perfected a miniaturized VNA. Figure 4.12 shows Stolar's VNA electronics (Millennium Board) on top of an HP 4369A VNA.

Figure 4.12. Stolar VNA and an HP 4396A VNA

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[2] Chufo, R. L., "Noncontacting coal and rock thickness measurements with a vector network analyzer," *Proceedings of the RF Expo East Conference*, Tampa, Florida, 1992, pp. 41–50

The test setup for an SFR is shown in Figure 4.13. Salt blocks were stacked together on top of wooden crates to form a wall of salt 23 ft long, 5.7 ft wide, and 3.7 ft tall. The fact that the width and the height of the salt wall are small causes the salt wall-air reflections to be noticed after a short travel distance from the antenna. In other words, after the wave is launched into the salt wall, the beam diverges and reflects from the wall-air interface, causing reflections to be prominent after a relatively small travel distance. Individual air gaps between salt blocks also contribute to the reflection of the wave. On average, each salt block was 8.5 inches x 9.5 inches x 11 inches, but the salt blocks were not uniform all the way around due to the way their mold is formed. Unfortunately, this causes air gaps between the salt blocks, as can be seen in Figure 4.13.

Figure 4.13. VNA and wave guide antenna test setup

The simplest method of data processing an SFR is by converting its frequency-domain information to an impulse response by an inverse FFT algorithm. A change in the phase of the time-domain (impulse) response indicates the presence of a scatterer, whereas the magnitude of the impulse response corresponds to the size of the scatterer.

A waveguide antenna was used to obtain data from 0.9 to 1.1 GHz at 51 equally spaced frequency steps, corresponding to a range of 50 ft in salt with a 1-ft resolution. The data, obtained by an Agilent 8753 VNA with a dynamic range of 110 dB, were then passed through an inverse FFT routine using the Matlab code of Appendix A. This code assumes a relative dielectric constant of 6 for the salt. The Matlab-processed data are shown in Figures 4.14 and 4.15. It properly shows the presence of a scatterer (the end of the salt wall) at the distance of 23 ft, indicated by the variation of phase response versus distance in Figure 4.14.

The amplitude response of Figure 4.15 is typical of a wideband radar: the features close to the radar antenna are obscured due to the step response of the wideband radar. Most of the reflected signal's energy is concentrated at the beginning of the transformed signal and time-gating is usually performed. This masks the response from the nearby scatterers. Stolar's HS with Resonant Microstrip Patch Antenna (RMPA), HS-RMPA, is a narrowband system that can detect nearby scatterers. We believe HS-RMPA, in addition to the wideband HS-Radar, will provide the additional reliability of void detection as the HS-RMPA can be calibrated to detect voids that are closer than 10 ft. The combination of these systems will enable detection over the full range of 0 to 20 ft ahead of mining. HS-RMPA can also provide a measurement of the relative dielectric constant of the coal, which is a more practical option than Chufo's method of moving the antenna with a positioner.

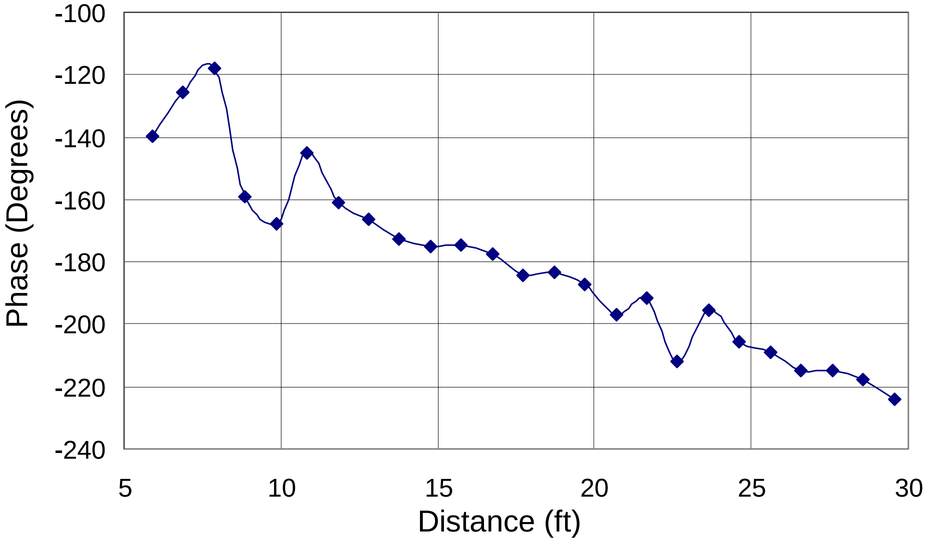


Figure 4.14. Measured phase angle results from the experiments in salt

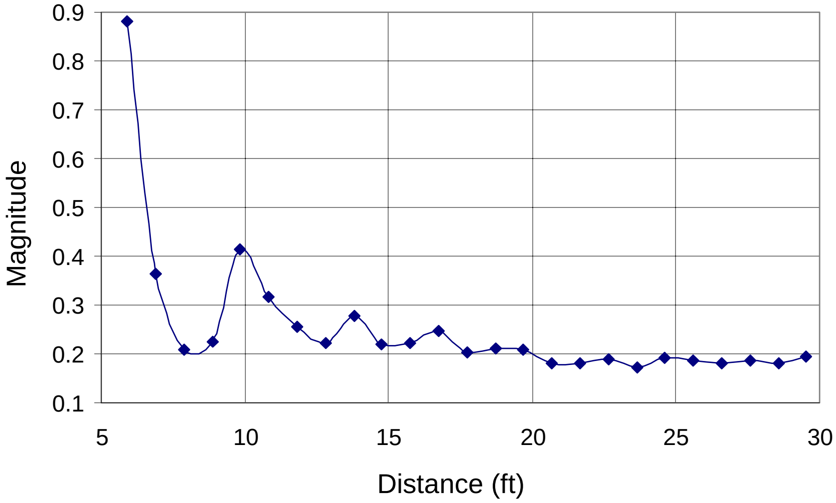


Figure 4.15. Measured magnitude results from the experiments in salt

On the strength of the Cook and Chufo works cited above and the Phase 1 data Stolar collected and analyzed, the concept of using SFR technology for detection of voids 20 ft ahead of mining is feasible. In addition to HS-Radar, the HS-RMPA (shown in Figure 4.16 during salt block testing similar to the HS-Radar tests) will also provide reliable void-detection capability for shorter ranges such as 0 to 10 ft. Having two systems will also provide an added dimension of safety and reliability since the HS-RMPA can be a backup to HS-Radar. As a mining machine moves toward a void, a decision-making algorithm will detect the void and shut down the machine's forward advance automatically. Such a feature is under a Stolar patent. Stolar will move forward to Phase 2, as outlined in the work plan. Phase 2 will include in-mine tests as well as updates to the Millennium Board.

Figure 4.16. The HS-RMPA (hand-held and machine mounted) were tested during salt block experimentation in the Stolar laboratory. This experimentation was performed in parallel to the HS-Radar work.

4.5.2 SmartBit Development

The SmartBit is an in-situ cutter-bit monitoring device that can be used to sense the rock interface based on the forces observed at the bit tip. As mining operations progress toward telemining and autonomous procedures, the need for machine performance monitoring increases. Presently, through a combination of vision, sound, and other subjective observations, an operator attempts to optimize the mechanical excavator's operation. As the operator is moved away from the face in the case of telemining or completely removed for autonomous operation, the qualitative sensory input is lost. This lost information must be replaced with quantifiable sensory input, such as chip-formation detection. SmartBit sensors have been developed to provide sensory output from all cutting implements on a mechanical mining machine using either radial or conical bits. The piezoelectric film sensor, used in the SmartBit, performs in a fashion similar to a dynamic strain gauge allowing monitoring of the loading state of an individual bit. Along with external circuitry, the sensor outputs a measurement of the force impulses experienced by the bit during the cutting and fracture of the rock. Chip formation can be predicted with high confidence (>80%) through the analysis of the load waveforms associated with bit/rock interface monitoring provided by SmartBit sensors.

The original project goal was the design and implementation of a sensor that could detect the individual health of mechanical excavation cutting implements, as well as being capable of directly monitoring the cutting process. During discussions with industrial sponsors, it became clear that optimization of machine performance is the most important objective for them. The sensor system developed in this research is intended to address all of these issues. The development of the sensor system can be subdivided into two parts: (1) the development of the physical transducer system, and (2) the development of the algorithms and software to interpret the signals received from the transducer.

As a first step in the design of the sensor system, a finite element analysis (FEA) was conducted to develop an understanding of the sensitivity of the physical structure to the loads being experienced. A model was developed to simulate the bit, block, and mounting plate system of a bore miner. The model began as a three-dimensional solid computer-aided design (CAD) model for each of the parts. A finite element mesh was then applied to transform the model into a representation appropriate for analysis using FEA code. The graphics in Figure 4.17 are the models in their various stages of development. The initial model includes the shank on the bit, which was intended to fit into a slot in the bit block. This proved to greatly complicate the model due to complicated meshing between complex surfaces, such as the bit shank and bit block slot and, therefore, was modified. The shank and slot were removed from the model and the bit was attached to the now smooth top of the bit block. While this is a great reduction in the model's complexity, the effect on the model's results is negligible due to the location of model measurements.

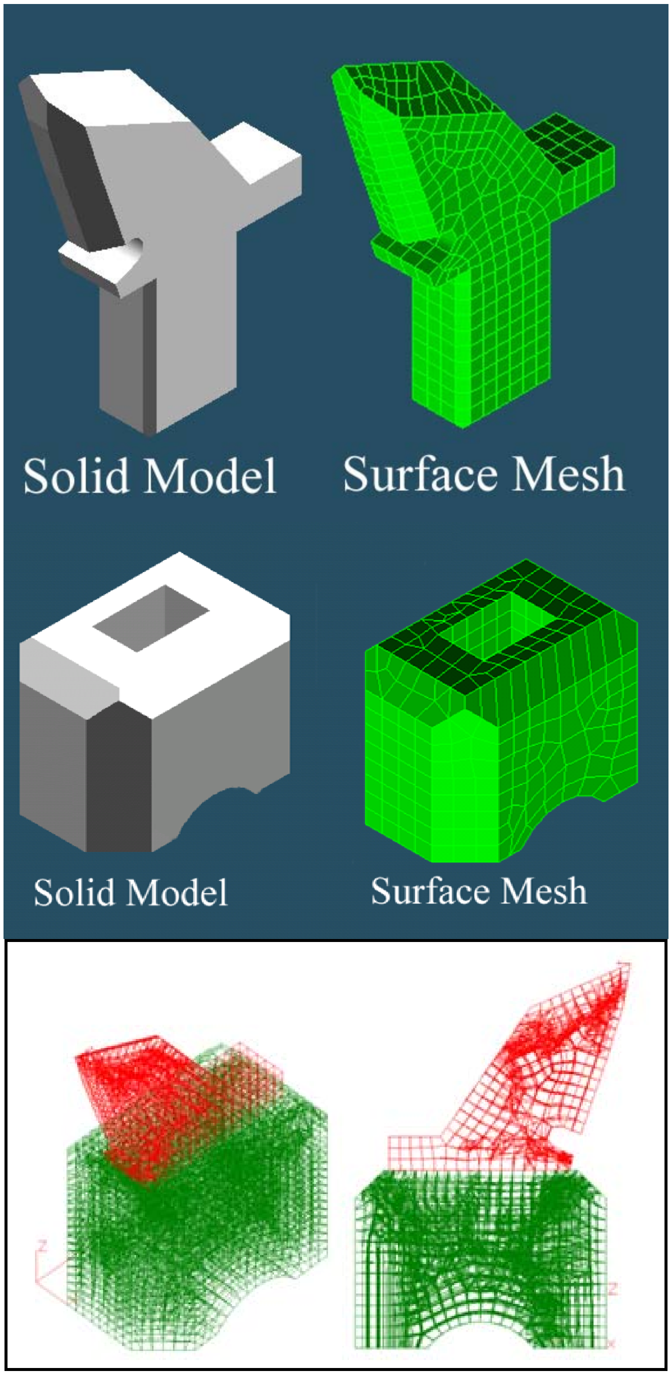


Figure 4.17. Stages of bit block FEA model including the solid model, surface model, and internal mesh of complete bit and block FEA model

The locations of possible sensor placement included the legs of the bit block and the bolts of the mounting plate. These areas were selected for the possible stress concentrations and their protection from damage during operation. The stresses/strains derived from the model were an order of magnitude less than the sensitivity of the commercially available strain gauges that were intended for implementation. The displacement values in the bit block legs were $\sim 10^{-8}$mm, while a fairly sensitive strain gauge is able to measure in the 10^{-6}mm range, using conventional data acquisition electronics. This displacement model is shown in Figure 4.18. The results of the FEA analyses demonstrated two important results: (1) the location of the sensor would have to be close to the action (i.e., on or near the bit), and (2) the level of strains that are incurred during operation are small and thus, the use of strain gauges would present significant challenges. For this reason, other types of sensors had to be investigated.

Figure 4.18. Bit/Bit Block displacement model

With strain gauges eliminated from the sensor selection, other sensor types were researched. These included piezoelectric film, capacitive, accelerometers, eddy current, and Hall effect. Piezoelectric film was selected as the most attractive solution. The selection was based primarily on cost and the lack of any required external circuitry. In the case of piezoelectric film, the current cost is very low (~$1-$4 per sensor). Also, piezoelectric film requires very limited external circuitry. Based upon these qualities, piezoelectric electric film was selected for physical testing and implementation, and ultimately as the final sensor type used in this research.

SmartBit sensors use the piezoelectric film in a strain gauge format. The film behaves as a *dynamic* strain gauge, which requires no external power source. The sensitivity of these sensors is also much greater than standard strain gauges. However, piezo-film's major limitation is its poor behavior in low frequency applications. This can be overcome with external circuitry, but in the case of SmartBit sensors this is unnecessary due to the algorithm developed for data processing.

The piezoelectric film can be modeled as a load-dependent voltage source in series with capacitance. When a load such as a measurement device is applied, the circuit forms a divider circuit with high-pass filter characteristics, where the time constant τ (in seconds) is equal to the product of resistance R (in Ohms) and capacitance (in Farads), i.e., regulation and control (RC). The cutoff frequency of the RC high-pass filter is given by the following equation:

$$f = \frac{1}{2pRC}$$

where, R is the measurement devices input resistance and C is the capacitance of the piezo-film which is given by the equation,

$$c = \frac{A}{t}$$

where ε is the permittivity of the film, *A* is the area of the film's electrodes, and *t* is the film's thickness. This value can also be verified by direct measurement. Operation below the cutoff frequency will cause the circuit to behave as a differentiator.

A differentiator can be described by the following equations. The voltage across C is designated as $V_s - V$ where V_s is the voltage source and V is the voltage across the input impedance of the measurement device, therefore,

$$I = C\frac{d}{dt}\left(V_S - t\right)\frac{V}{R}$$

and if dV/dt << dVs/dt, then

$$C\frac{dV_S}{dt} >> \frac{V}{R}$$

and by solving for V,

$$Vt = C\frac{d}{dt}V_S t$$

For dV/dt << dVs/dt, the time constant $\tau = RC$ must be sufficiently small. However, if the load R is too small, it will act as a "short" and ground the signal. In the case of piezo-film, it is this issue that is central to many of the implementation difficulties. Therefore, the output (voltage across R) is proportional to the rate of change of Vs (piezo-film voltage source). This effect can be seen in Figure 4.19. A square wave is input into the circuit and the resulting waveform of V can be seen. The small spikes are generated by the transitions in the square wave. The loading that the mechanical excavation bit is expected to experience will be similar to a saw-toothed waveform. The effect of a differentiator circuit on a square wave input can be seen in Figure 4.19 and on a saw-toothed wave input in Figure 2.20. Instead of being an infinitely narrow impulse as in the case of a square wave, a wider pulse is output.

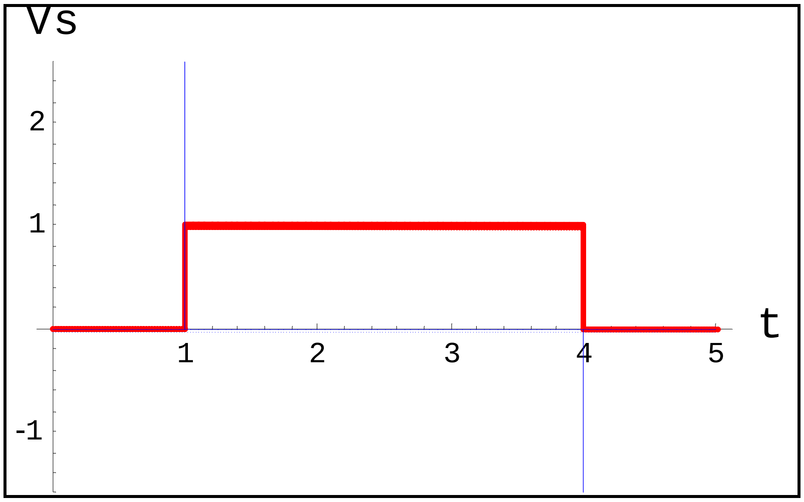


Figure 4.19. Square wave input (red) with differentiator output (blue)

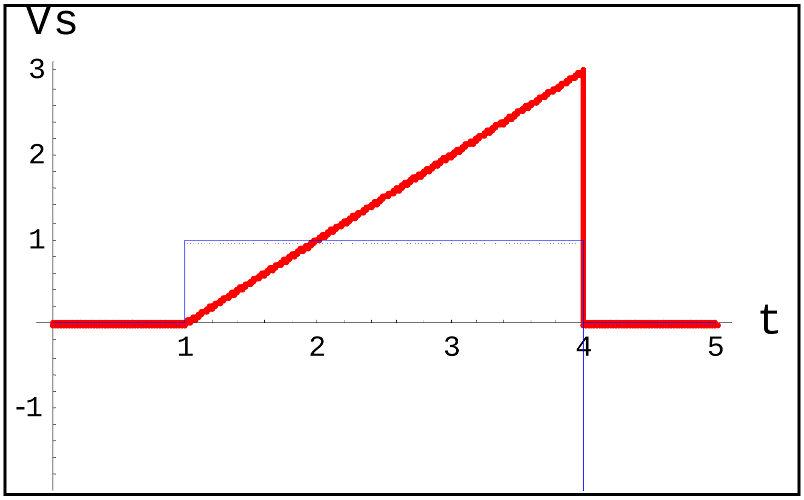


Figure 4.20. Saw-toothed wave input (red) with differentiator output(blue)

The initial test of the piezoelectric film was completed using a Tinius Olson hydraulic loading machine. The tests were motivated by a need for a controlled experiment to verify the operation of the piezo-film. A cyclic loading algorithm was developed in LabView for the tests. The sensor mounting was prepared in different sample forms, with both successful and unsuccessful outcomes, as discussed below. The forms differed only in the mounting of a standardized sensor. The data collected from the tests were subjected to limited processing. The results provided qualitative proof of sensor operation. Primarily, these tests, through trial-and-error, developed the mounting procedures used for SmartBit sensors.

The algorithm developed by Bryan Walter in LabView controls a proportional hydraulic servo-valve. Using the feedback of a pressure transducer, the pressure in the load cylinder is rapidly cycled between the two set points of the program. These set point pairs need only lie within the linear range of the mechanical components. The loading rate can also be controlled, which is important due to the dynamic loading needs of the piezo-film and measurement circuit pair. This is due to the differentiator behavior inherent in the circuitry.

The data collected from the load tests were processed in a very limited manner using Mathematica routines. The routines cleaned the signals slightly and produced plots of the signal. The data sets of the tests were inspected only for verification of film operation. Qualitatively, the measured response of the piezo-film sensors tracked that of the known input from the driver program. Because the frequency at which the system was driven was below the cutoff frequency of the RC network, the output of the sensor demonstrates the differentiator behavior mentioned previously.

Initially the film was loosely placed between two thin aluminum plates, but the piezo-film critically failed before data were collected. This was due to a slight roughness in the aluminum surface. To remedy this flaw, half-inch steel plate was prepared to accept the piezo-film samples. The surfaces of the plate were milled to square each block. The surfaces where the piezo-film was mounted were further prepared using a surface grinder. The piezo-film was glued to the surface as further protection. This design, shown in Figure 4.21, proved to be a successful mounting procedure and has been used for full-scale bit testing.

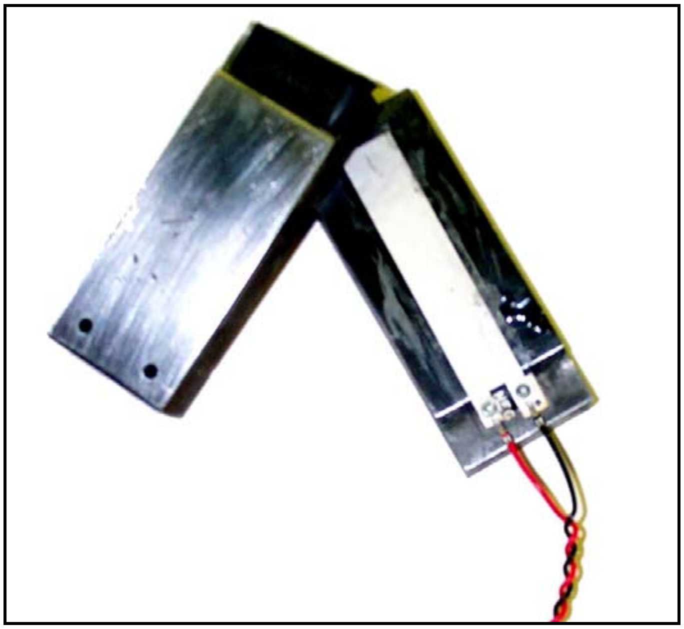


Figure 4.21. Piezo-film mount

Mounting of the piezo-film in radial bit block hardware was initially viewed as a fairly simple task. However, this assumption was rapidly proven wrong. The preliminary plan was to machine a slot into the bit block. This slot would change the shank hole of the block from a rectangular opening to a T-shaped slot as seen in Figure 4.22. A sandwich of two steel plates and the piezo-film would then be interference fit into this slot. This plan could still be used if full radial cutter head implementation of the sensor occurs. The t-slot sensor-mounting layout is unacceptable for limited laboratory tests due to costs, which arise from the difficulty of modifications of the hardware. This problem was circumvented through the development of a custom Linear Cutting Machine (LCM) saddle. The saddle includes mounting hardware for the piezo-film as well as a rigid shank hole to act as a bit block.

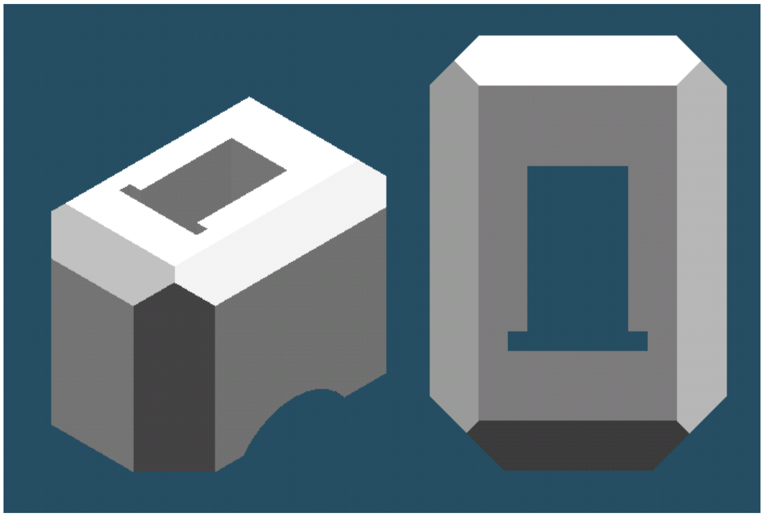


Figure 4.22. Proposed bit block modification

The saddle is designed as an I-beam welded to a saddle plate, as seen in Figure 4.23. The saddle plate is 1.5"-thick plate with mounting holes for the LCM. During operation, the plate transmits the mounting hardware's load to the LCM's load cell. The I-beam was built using 6" x 1" steel plate. A slot was milled into the end of the I-beam to act as a shank hole in a bit block. The slot was made larger than a standard shank to accommodate the piezo-film hardware in the form of two steel plates encasing a piezo-film sensor. A recess is milled in the I-beam for wiring. Two sections of the 6" x 1" plate are used to complete the shank hole. These caps required spacers to increase the slot width to that of a manufactured bit block.

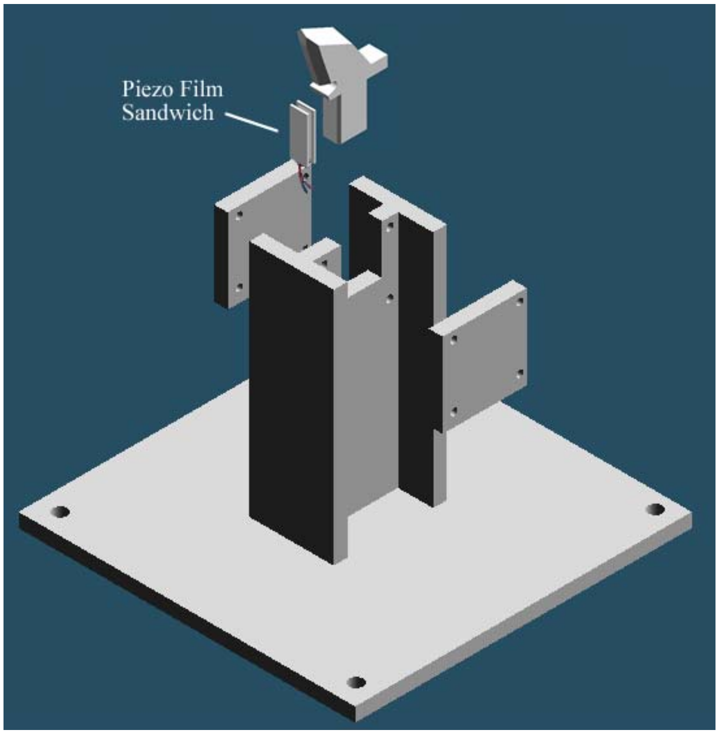


Figure 4.23. SmartSaddle solid model

The piezo-film, which is sandwiched between two quarter-inch thick plates, is mounted in the front side (nearest side to direction of travel). The film is loaded by a rocking action of the bit, which occurs due to the loose running fit of the bit shank and bit block. While this does not load the film normal to its surface, the interaction provides enough compressive stress on the film for sensor operation.

The SmartSleeve mounting hardware uses piezo-film as a thin load washer. The initial concept mockup can be seen in Figure 4.24. Four thin aluminum plates protect the piezo-film. The center two plates have notches for the leads of the piezo-film. These plates sandwich the film and are glued together. The outer two plates are wear plates for protection. The sensor was tested for operational success with a Tinius Olson machine.

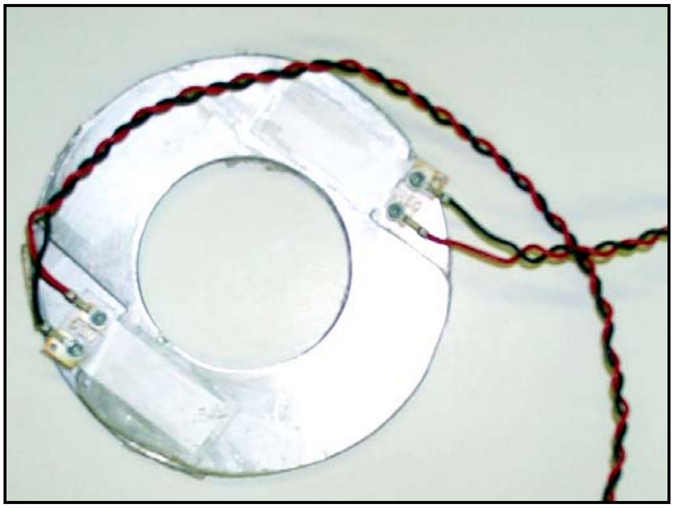


Figure 4.24. SmartSleeve mock-up

A much more hardened sensor was necessary and was developed late in the project. The concept is similar to the aluminum plate model. A wear sleeve was turned on a lathe to remove a portion of its shoulder. Piezo-film was custom fit to the surface and affixed. A custom washer was machined to complete the sensor sandwich. The leads from the sensor are routed through a hole in this washer. The washer is also affixed to the sensor and wear sleeve. Preliminary tests are currently being conducted on this sensor.

The piezo-film requires ancillary electronics to stabilize the sensor and condition the sensor output. The film's electrical output is in a measurable voltage range, but the current produced by the film is so low that it causes difficulties in manipulation and input of the signal to data acquisition systems. In addition, the piezo-film tends to build up charge during operation. Both of these problems required a solution before initial tests could begin. The preliminary fix for charge buildup was to place a bleed resistor in parallel with the film to bleed the charge. The film requires a large input impedance (>MΩ) for measurement; if the resistance value is too small, the bleed resistor will act as a short in the circuit. Therefore, the solution of a simple carbon resistor did not work due to the difficult of obtaining appropriate resistance values. An instrumentation amplifier was proposed as a solution. An Analog Devices AD620 instrumentation amplifier was selected (AD620 2002). The amplifier is used at unity gain, and, therefore, acts only as a buffer to condition the signal and act as a bleed resistor. Amplifiers tend to be described as having infinite input impedance, and, in the case of most circuits, this is true. The AD620 has low input impedance compared to most operational amplifiers. The AD620 has a 10 GΩ, whereas other amplifiers may have orders of magnitude greater input impedance. This can be viewed as a limitation of the amp, but in this application is an advantage. The input impedance of the amp acts as a bleed resistor in the sensor circuit. The other effect of the amp is to increase the current of the signal to allow easier integration with other hardware.

Using the known components of the sensor, a wiring diagram (shown in Figure 4.25) and equivalent circuit were developed. This circuit has a cutoff frequency of 0.012 Hz and the decay (roll off) of the signal is described by a first order system with a time constant of $\tau = RC = 13$ s. This decay was experimentally verified.

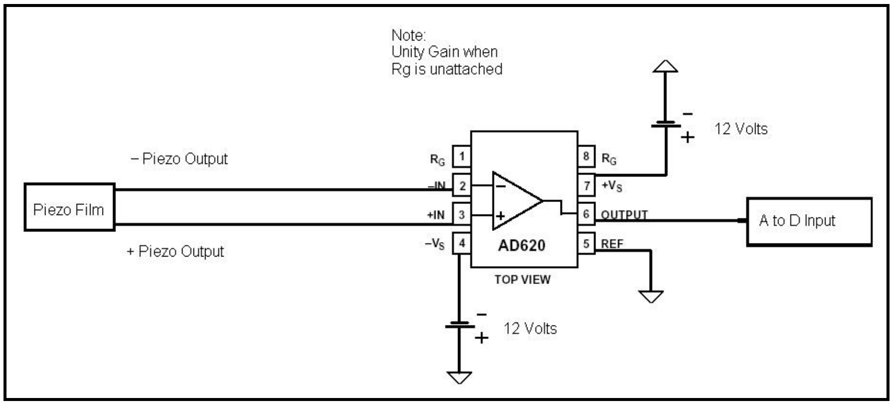


Figure 4.25. Amplifier wiring diagram

The output from the amp after a single loading of the sensor can be seen in Figure 4.26. The time constant is estimated by the time at which the signal has decayed to 37% of its original value. A time constant of 0.72 seconds has been estimated; therefore, the estimated cutoff frequency is 0.22 Hz. The difference between theoretical and actual is a factor of twenty. The difference is believed to be due to inaccuracies in the value of the AD620's input impedance.

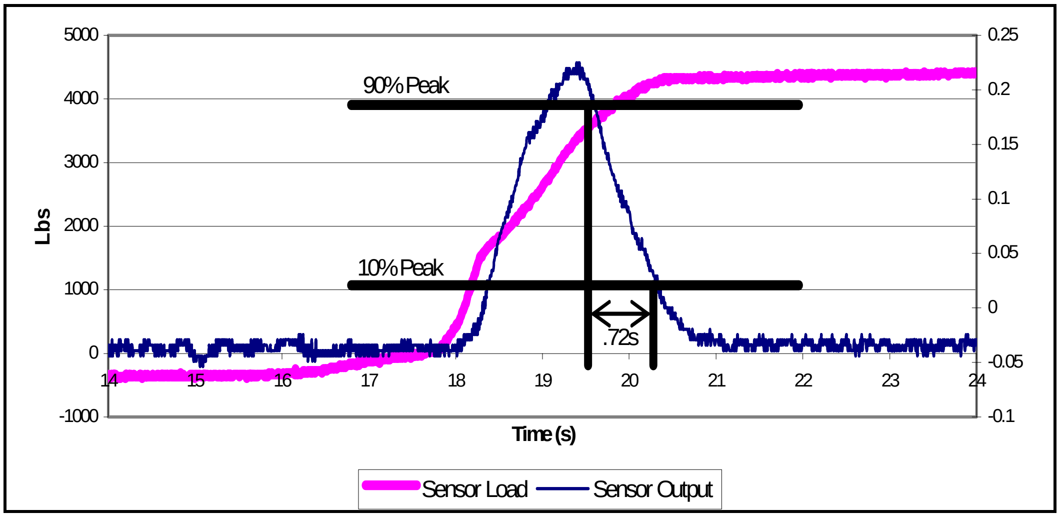


Figure 4.26. Piezo-film load waveform for single loading

The key to making the SmartBit a viable sensor on the cutter drum is to effectively monitor the bit loading in real time. After traditional machine monitoring techniques, such as Fourier analysis, failed to reveal bit/rock interface information from load cell data acquired with the LCM, a processing technique was developed. The Pulse Count Algorithm (PCA) through the use thresholds was able to predict the formation of chips at the bit/rock interface. This prediction can be made with a >80% confidence. Presently, the PCA has only been applied to LCM load waveforms, but custom SmartBit sensors will produce data in later tests to be processed by the PCA.

Presently, SmartBit prototypes, based on piezoelectric sensors, exist for both radial and conical bit types. The sensor selection was based on FEA. This analysis directed the sensor selection towards ultra stain-sensitive sensors due to the FEA model's strain measurements of ~10^{-8}mm, which is two orders of magnitude less than the sensitivity of commercially available strain gauges. Piezoelectric film was selected as the sensor. The film behaves as a *dynamic* strain gauge, which requires no external power source. Laboratory prototypes have been constructed and tested.

Before in-situ testing can occur, the device must be designated "intrinsically safe" by Mine Safety and Health Association (MSHA 1995). "Intrinsically safe" designation for piezo-film applications is defined as a maximum energy allowed from an impact. A 2-kg steel rod dropped from a height of 1 meter provides the impact energy of 19.6J. The maximum allowed energy output for an I.S. piezoelectric device is 1500 μJ. From preliminary tests, our sensors have a safety factor of 10–20.

The work reported here demonstrates that a piezo-film sensor, in conjunction with the proper algorithms, can predict the occurrence of chip formation and the size of chip being produced as a bit is drawn through rock. This system, if it proves to be robust in an operational environment, should be the basis for several new and exciting developments for mechanized mining.

The future studies for SmartBit sensors primarily will be implementation and hardening of the sensor. Calibration for both conical and radial SmartBit sensors using piezo-film data will be required. As the sensor reaches a final design state, more complex sensing capabilities will be explored.

5. Results – HS Commercial Installations

5.1 HS-3 Field Installations

The HS program involved three main phases of activity: engineering, product development, and field testing. The first two activities were discussed at length in Sections 3 and 4 of this report. Without direct coal mining partnership under this program, much of the field testing occurred under the auspices of technology demonstration programs with individual coal companies. These programs were either commercial sales, involving the monthly lease of an HS-3 system, or they were funded demonstration programs involving the implementation HS on private mining equipment and subsequent monitoring of HS capabilities and benefits relating to clean coal issues (funding from State or collegiate agencies).

During this 3-year program a total of 14 Horizon Sensor installations have occurred. These installations, both commercial and demonstrative, are listed below in chronological order. This list includes HS Version, Mining Machine Type, Mine Site, Mining Company, and Date.

- HS-CM, Joy HM31, Brandspriut-1 Mine, SASOL Fuel, May 2001
- HS-CM, Joy 12CM, Monterey Coal Company, Exxon Mobil, January 2002
- HS-CM, Joy 12CM, Twentymile Coal Company, RAG America, March 2002
- HS-BM, Marietta Borer Miner, Green River Mine, FMC Trona, March 2002
- HS-LW, Joy 4LS Shearer, Monterey Coal Company, Exxon Mobil, June 2002
- HS-CM, Joy 12CM, Oxbow Mine, Oxbow Mining Company, July 2002
- HS-LW, Joy 4LS Shearer, Monterey Coal, Exxon Mobil, September 2002
- HS-LW, Joy 4LS Shearer, Deserado Mine, Blue Mountain Energy, January 2003
- HS-CM, Joy 12CM, West Elk Mine, Mountain Coal Company, March 2003
- HS-LW, Joy 7LS Shearer, Century Mine, Ohio Valley Coal Company, July 2003
- HP-CM, Joy 12CM, Monterey Coal Company, Exxon Mobil, September 2003
- HS-HW, SHM Low-Seam, Logan County Mine, Massey Energy, November 2003
- HS-CM, Joy 12CM, SUFCO Mine, Southern Utah Fuel Co., December 2003
- HS-LW, Joy 7LS Shearer, Robinson Run Mine, CONSOL Energy, December 2003

5.2 Commercial Lease Programs

The following sections outline commercial installations involving leased Horizon Sensor systems, their performance testing, and commissioning.

5.2.1 SASOL Fuel: HS-CM Joy HM31

The first HS-3 system was used in the field in May of 2001. The system was installed on a Joy HM-31 (modified 12CM for high-seam applications) at SASOL Fuel's Brandspruit-1 Mine in South Africa. Stolar had worked with SASOL on the original HS-1 program and this project was essentially a follow-up effort.

The electronics for SASOL's machine were manufactured by Stolar and sent to the mine site. The enclosures, however, were South African designed and certified based on South African standards and compliance guidelines. While not drastically different in design, there were some incompatibilities that created problems and delays. The HS-3 system for SASOL is shown in Figure 5.1 on their HM-31 continuous miner. The Display, Generator, and Sensor electronics were standard at the time; only the enclosures were specific to the application.

Figure 5.1. Installation of HS-3 on an HM-31 continuous miner at SASOL Fuel in May 2001

The underground field testing of the unit proceeded on schedule, and several software changes were made on site to better accommodate the antenna tuning process and methods of initialization and calibration. However, when the unit saw hard cutting conditions in normal production periods, a serious design flaw was realized.

During the system's second week of mining, the sensor lens failed under the impact of mined debris and was significantly deformed. Over the course of several shifts, the lens itself was pressed into the sensor enclosure and crushed the sensor electronics, as seen by the damage in Figure 5.2. It was then realized that the lens material used by the South African contractors was not the same material specified by Stolar. The material used was a polyethylene, similar to nylon, commonly used for abrasion resistance on mining machinery by SASOL. It lacked the strength and impact resistance of the material (ballistic polycarbonate) used by Stolar in its US product line. The South African contractor claimed that the polycarbonate specified in the assembly drawings was not available as an approved material in housing fabrication. Using the proper ballistic polycarbonate would require 6 months of certification.

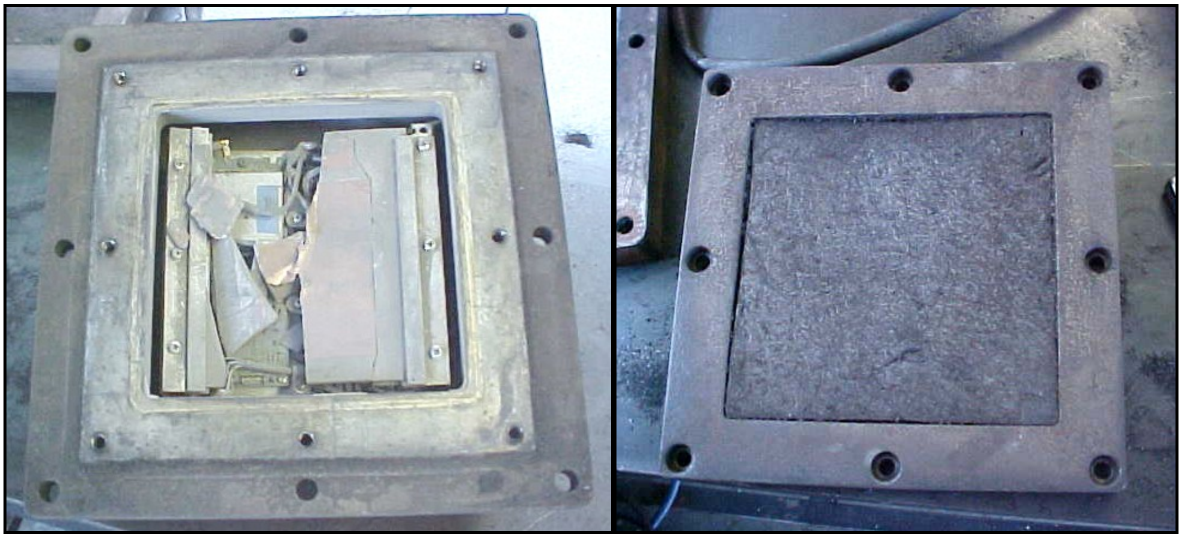


Figure 5.2. Damaged HS-3 sensor electronics resulting from lens failure on SASOL Fuel's mining machine

Stolar and SASOL did elect to replace the electronics and start the certification process on the polycarbonate lens. However, after 1 month, mine management took the mining machine that was equipped with HS hardware out of the normal development section of the mine and put it into duty on pillar extractions in a board-and-pillar section of a different mine. This effectively ended the testing phase of the program. At the same time, SASOL's technology group began to work on an agile mining machine project involving gyro-based guidance systems, and ties were severed with the Stolar Horizon sensor program. In subsequent discussions with SASOL, it was apparent that they consider their agile mining system (similar to Joy's JNA system, only with guidance controls) to be a competitive technology to the Horizon Sensor, even though it does not actively sense the coal horizons.

5.2.2 Monterey Coal Company: HS-CM Joy 12CM12

Installation of an HS-CM system on a Joy 12CM12-10A at Monterey Coal Company began Friday, January 11, 2002, and was completed on Tuesday, January 15, 2002. The total installation time was approximately 8 hours, although nearly 10 more hours were spent fabricating a protective steel cage and plates for the Horizon Graphics Unit (HGU) and GUI Modem Aerial (GMA) antenna as well as random double checks and tool problems. In addition, several hours were spent welding boxes and brackets to the cutter drum during machine-shop rebuild of the CM 8 months prior. Once underground, it was determined that additional fabrication was needed to protect the HGU, and two more shifts were devoted to that. The installed system, shown in Figure 5.3, proved rugged, dependable, and maintenance free during duration of testing.

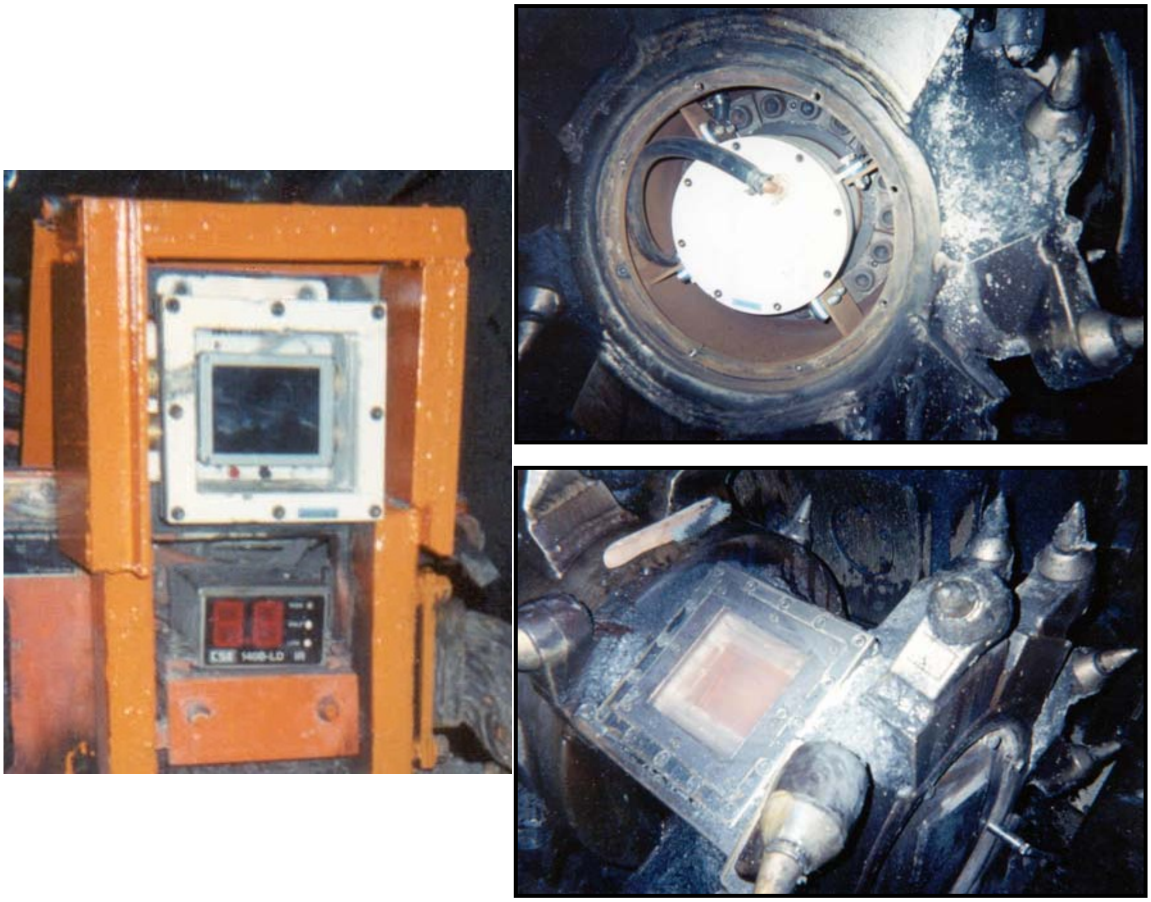


Figure 5.3. HS-CM system installed on a Joy 12CM12-10A and in use at Monterey Coal Company. Horizon Graphics Unit (HGU) on the rear of the CM (left); Horizon Power Unit (HPU) generator within the cutter drum (upper right); and the Horizon Sensor Unit (HSU) on the surface of the cutter drum (lower right).

The system was checked and double-checked to ensure that all electrical and software functions were performing as intended. Several series of tests were conducted to verify performance on a modular and full-system level. The tests were conducted Tuesday and Wednesday, January 15 and 16, 2002. Highlights included:

- The measurement window was set up using the trigger light emitting diode (LED) to indicate Triggering Window position and stability. A data average of 3 created a 5–7 degree window at TDC and BDC; the window was stable.
- The Measurement Modes efficiently transitioned from Roof to Floor Modes when the cutter boom passed through mid-angle. Sump Depth and Forward Detector Modes were not tested.
- Data transmission and command timing were found to be stable and dependable. The location of the GUI aerial antenna proved sufficient for reception, but further experimentation may lead to the aerial being relocated back towards the GUI (if not completely inside).

- The power generator output proved stable and reliable with default torque on the detent clutch springs. Pendulum position was stable with no detent loss on start-up (identifiable by modem LED fluctuation and/or trigger LED through lens assembly).

- The inclinometer angle proved stable and reliable. The boom was initialized at the horizontal and the inclinometer was positioned within its enclosure in such a way that its output was at a null (0 V out in the ±13-V range).

- GUI power reset timing was adequate. The GUI would reset itself during power trip, and flawless reboots were the norm. The AC diode did blow during a power surge in the section. While this may have protected our power board from damage, it also shorted the AC lines of the control box of the miner and wreaked havoc on the start-up circuitry of the mining machine. The burnt diode was removed to correct the short; additional testing should be done to determine better surge protection.

- The machine's dimensional parameters (boom length, drum diameter, drum speed, and inclinometer scale) were measured and entered into the Setup menu exactly. The measurements provided nearly perfect boom height/distance computation; therefore, the predicted mine height was accurate to within 1 inch.

- Resonant frequency and gain optimization was done once the HSU module was fully installed (battery cable and serial line routed through unpacked gland in lieu of generator cable). The resonant frequency was found to be 510 MHz at a gain setting of 16 dB.

The system functionality tests provided real-world proof that the system is performing as designed.

Time was spent working on antenna sensitivity and resonant frequency during the Functional Testing phase, and the calibration issues were worked out during the final testing day on Thursday, January 17, 2002. Highlights include:

- Water spray proved to be reconcilable and at this point water (low level) is not considered to be a problem. The resonant frequency of the antenna without water was 510.25 MHz under rotation (I=1000, Q=-500); with the water spray on, the resonant frequency dropped to 509.75 MHz (I=400, Q=-2100) and showed the same range of I/Q sensitivity to air-gap reduction.

- Air-gap-based calibration spirals for the system were analogous to lab versions. Coal-horizon-based calibration spirals are being catalogued and analyzed, but visual inspection of calibration points implied a wide point-for-point variation (imperative for prediction stability).

The best calibration results, shown in Figures 5.4 and 5.5, occurred when calibration points were stored immediately after coal perforation and clearance from the bit picks. The miner operator could bump the drum up or down through the coal seam during a calibration sequence allowing the air gap to clear (taking less than a single rotation) and the sensor to see only the uncut coal horizon directly as opposed to a layer or random crushed and saturated coal chunks.

This process may prove too difficult for an operator to perform on his own, and more investigation should be done to develop alternate calibration processes/methods.

Maximum predicted depth was reduced from 24 inches to 12 inches. The mine is only interested in leaving 1 inch of uncut coal on the roof, so focus will be put on maximizing prediction stability for the lower thickness.

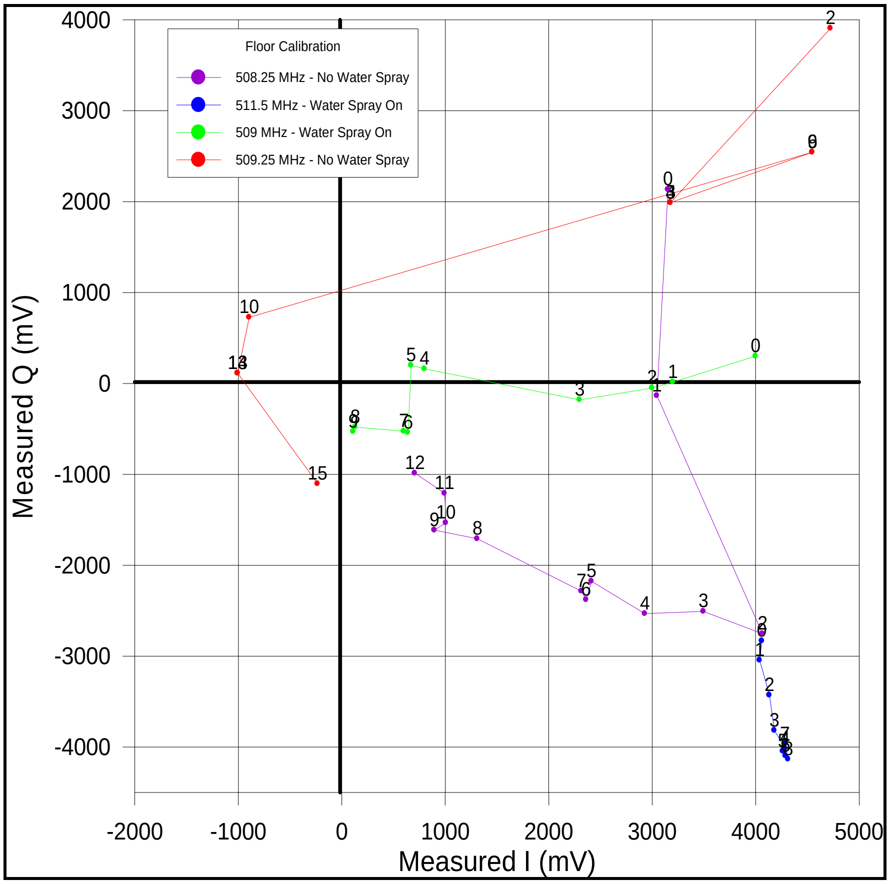


Figure 5.4. A series of HS calibration curves under differing frequency settings and water conditions as recorded during floor cutting of the coal seam at Monterey Coal Company

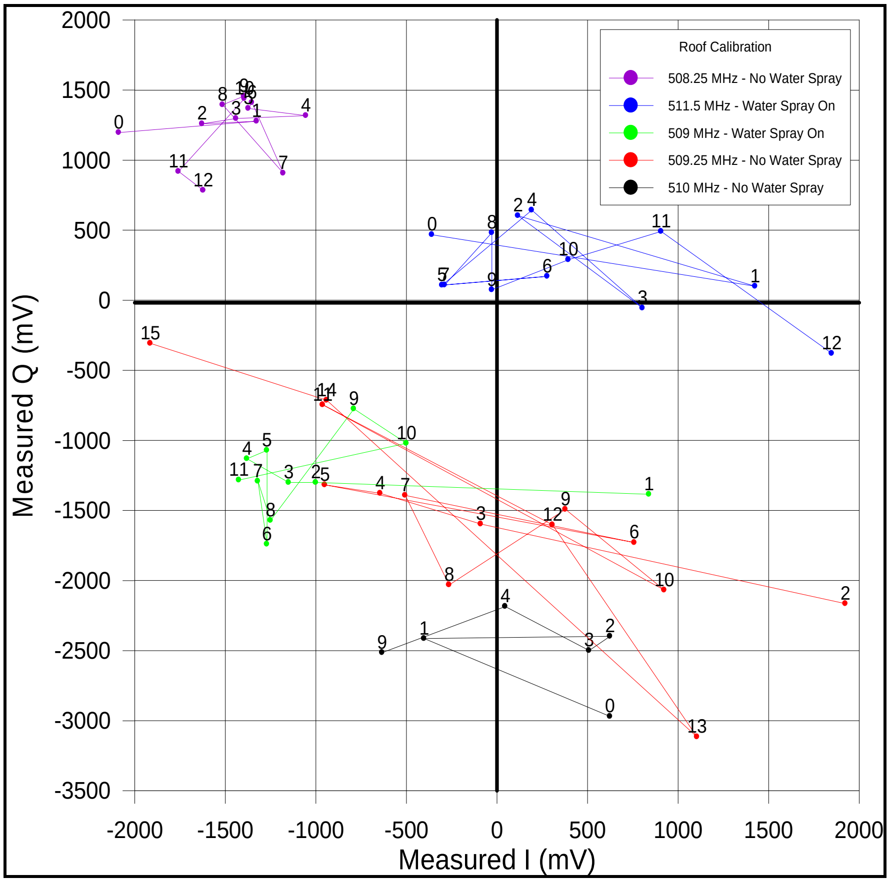


Figure 5.5. A series of HS calibration curves under differing frequency settings and water conditions as recorded during floor cutting of the coal seam at Monterey Coal Company

Mine height proved to be a critical tool for this particular mine at this point in their developmental sections. The coal seam is at present only 6 feet thick (and thinning inby), however, the section must maintain 7-foot 6-inch entries for machine clearance. Setting the GUI up to display mine height to the operator will save time, bit replacement, and rock reject numbers. This 90-inch mine height was accurately predicted on the HS provided that the body of the miner was relatively flat. The GUI graphics are being changed to indicate mine height in larger, easier-to-read font.

To test the prediction capabilities of the HS-CM system, a series of coal-cutting tests were designed that would allow uncut coal to be left in the roof or floor while logging thickness predictions over these areas. The actual thickness of the roof and floor coal could then be measured directly by hand for comparison to predicted values.

These tests were carried out in a section of the longwall panel gate roads that possessed only 5- to 6-foot coal thickness. Since mine height had to be a minimum of 7.5 feet, roof and floor coal had to be tested in different areas; roof coal was left uncut and bolted in one entry (required floor rock to be removed), while floor coal was left in another (requiring roof rock to be removed). The procedure for measuring coal is separated into the following roof and floor tests.

Floor Prediction/Verification Process per Cut

- While at the face, establish Floor Rock position, place drum on floor rock, and initialize boom
- Sump into top of face, cut down while performing HS floor calibration procedure
- Clean the face up after cut and position drum at a height above the floor that will leave the desired uncut coal thickness
- Sump into the face at this point to leave floor coal; log the thickness prediction and mark the rib for start position (0)
- Complete sump up to minimum mine height (7.5 feet); log Total Mine Height Reading at this position
- Continue forward cut with 3 to 4-foot sump depths to normal distance (20–25 feet); use floor predictions to limit floor cut to the desired range
- For each sump: mark position and reading # on rib; log forward position, log thickness prediction, and total mine height
- Log the calibration table when finished with cut
- Repeat all measurement logs for slab side as well
- Remove miner from entry and complete roof bolting; note any roof-fall thickness or floor disruption during bolting
- Drill/pick through the uncut coal to the floor rock at the positions held by the drum during data logging (center and left side of the entry)
- Measure coal thickness for addition to table and comparison to predictions

A single 25-foot cut was done to measure uncut floor coal and coal thickness ranged from 1 to 10 inches.

Roof Prediction/Verification Process per Cut

- While at the face, establish roof rock position, place drum on roof rock and initialize boom
- Sump into center of face, cut up while performing HS roof calibration procedure
- Clean the face up after cut and position drum at a height below the roof that will leave the desired uncut coal thickness
- Sump into the face at this point to leave roof coal; log the thickness prediction and mark the rib for start position (0)

- Complete sump down to minimum mine height (7.5 feet); log Total Mine Height Reading at this position
- Continue forward cut with 3 to 4-foot sump depths to normal distance (20–25 feet); use roof predictions to limit floor cut to the desired range
- Log the calibration table when finished with cut
- Repeat all measurement logs for slab side as well
- Remove miner from entry and complete roof bolting; note any roof-fall thickness or floor disruption during bolting
- Drill/pick through the uncut coal to the floor rock at the positions held by the drum during data logging (center and left side of the entry)
- Measure coal thickness for addition to table and comparison to predictions

A total of four 25-foot cuts were done to measure uncut roof coal and coal thickness ranged from 2 to 10 inches.

For each sump, a spreadsheet like that shown in Table 5.1 was used to record cutter head position and HS prediction measurements.

Table 5.1. Data collection for HS-CM verification testing at Monterey Mine

Cut #: 3	Operating Freq: 511.5 MHz
Uncut Coal Type: Roof	Machine: 44"diam, 162" boom, 60 RPM
Desired Thickness: <12"	Floor Init. Angle: -6.7
Test Location: Entry 3, XC-53	Roof Init. Angle: +10.3
Operator Name: Gary	Position of head: Slab side

Sump #	Distance (feet)	Thickness Prediction	Prediction Stability	Sensitivity (mV)	Mine Height Prediction	Actual Coal Thickness	Actual Mine Height
1	0	12"	12, 10	400	7'5"	11"	7'5"
2	2	12"	12, 10	400	7'5"	11.5"	7'4"
3	8	5"	5,6	500	7'9"	4"	7'10"
4	10	2"	2	540	7'11"	3"	7'11"
5	14	1"	1	540	8'1"	3"	8'
6	17	2"	2,3	540	8'1"	2"	8'1"
7	21	3"	3	540	8'1"	2"	8'
8	25	3"	3	540	8'1"	2"	8'1"

Five total cuts were performed using the test plan described: four uncut roof coal sections and one uncut floor coal section. The data gathered were used to generate the five bar graphs (Figures 5.6 through 5.10) showing predicted coal thickness versus actual thickness. The actual coal thicknesses, as well as mine height, listed in the data tables (and plots) are average estimates made with a tape measure. The exact position of a planar boundary in the seam is often difficult to delineate due to irregularities in the cut (scoured) surface.

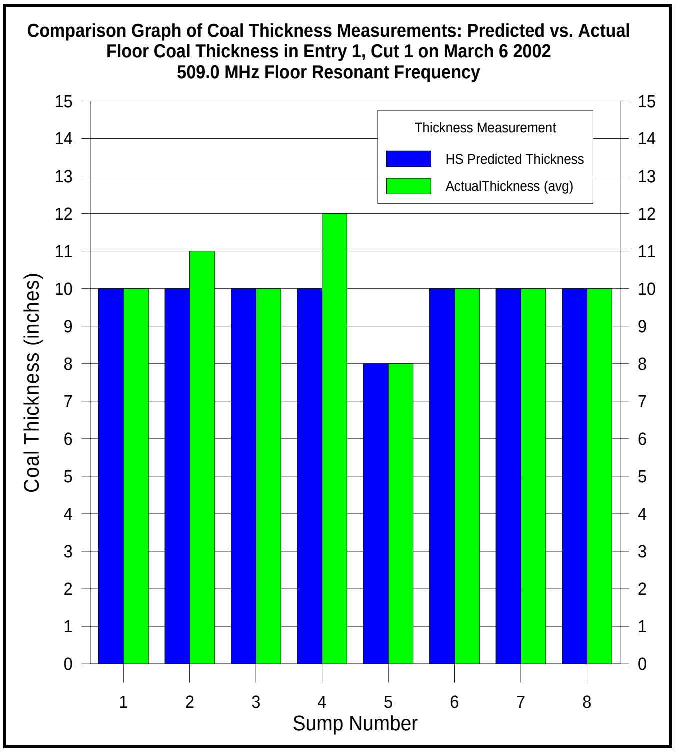


Figure 5.6. Uncut floor coal prediction – Entry 1, Cut 1

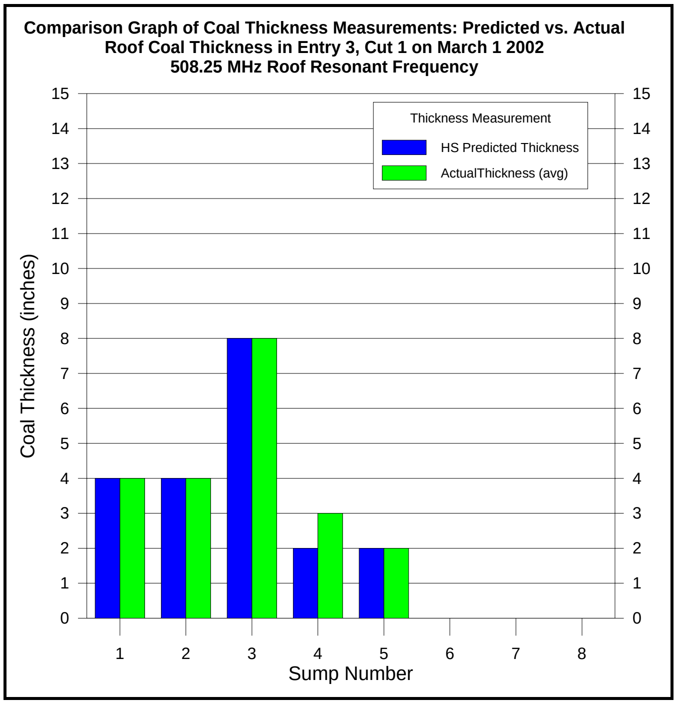


Figure 5.7. Uncut floor coal prediction – Entry 3, Cut 1

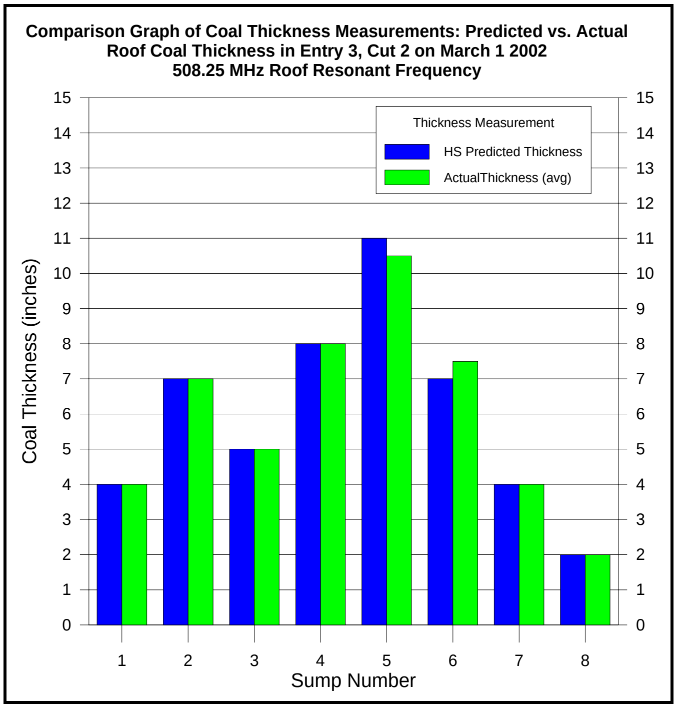


Figure 5.8. Uncut floor coal prediction – Entry 3, Cut 2

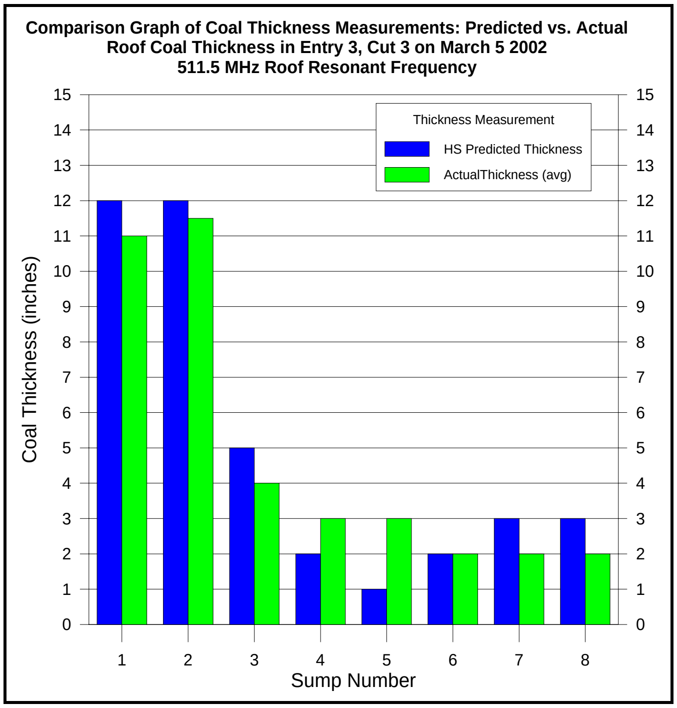


Figure 5.9. Uncut floor coal prediction – Entry 3, Cut 3

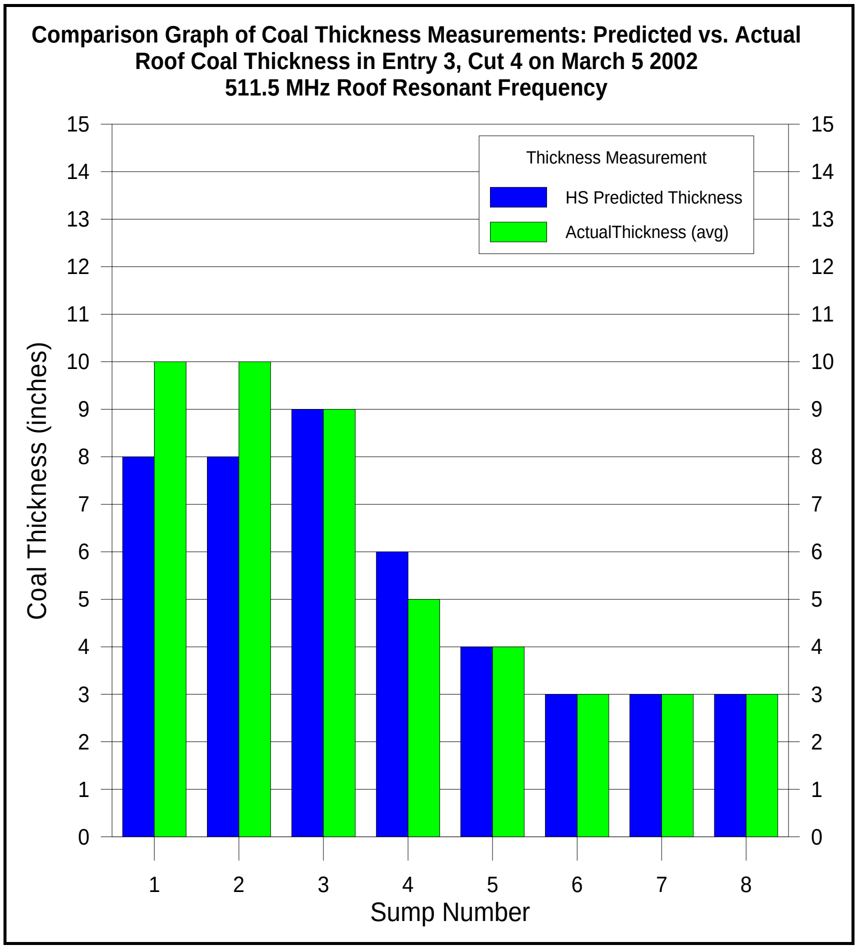


Figure 5.10. Uncut floor coal prediction – Entry 3, Cut 4

The resulting verification data can be represented in an accuracy graph that shows predicted uncut coal thickness as a function of actual measured thickness. A perfect prediction lies on the diagonal line from lower left to upper right. The accuracy plot for the Monterey Mine HS verification testing is shown in Figure 5.11.

A record of mining history for the Monterey continuous miner during the verification and commissioning period is shown in Table 5.2.

Table 5.2. CM mining history during HS commissioning

Dates	1/12 to 2/2	2/3 to 2/8	2/9 to 3/8
Operational Hours	174	55	254
Raw Coal Cut	29606	8575	31670
Clean Coal Cut	19541	5680	21924
Entry Footage Cut	3959	1260	4781

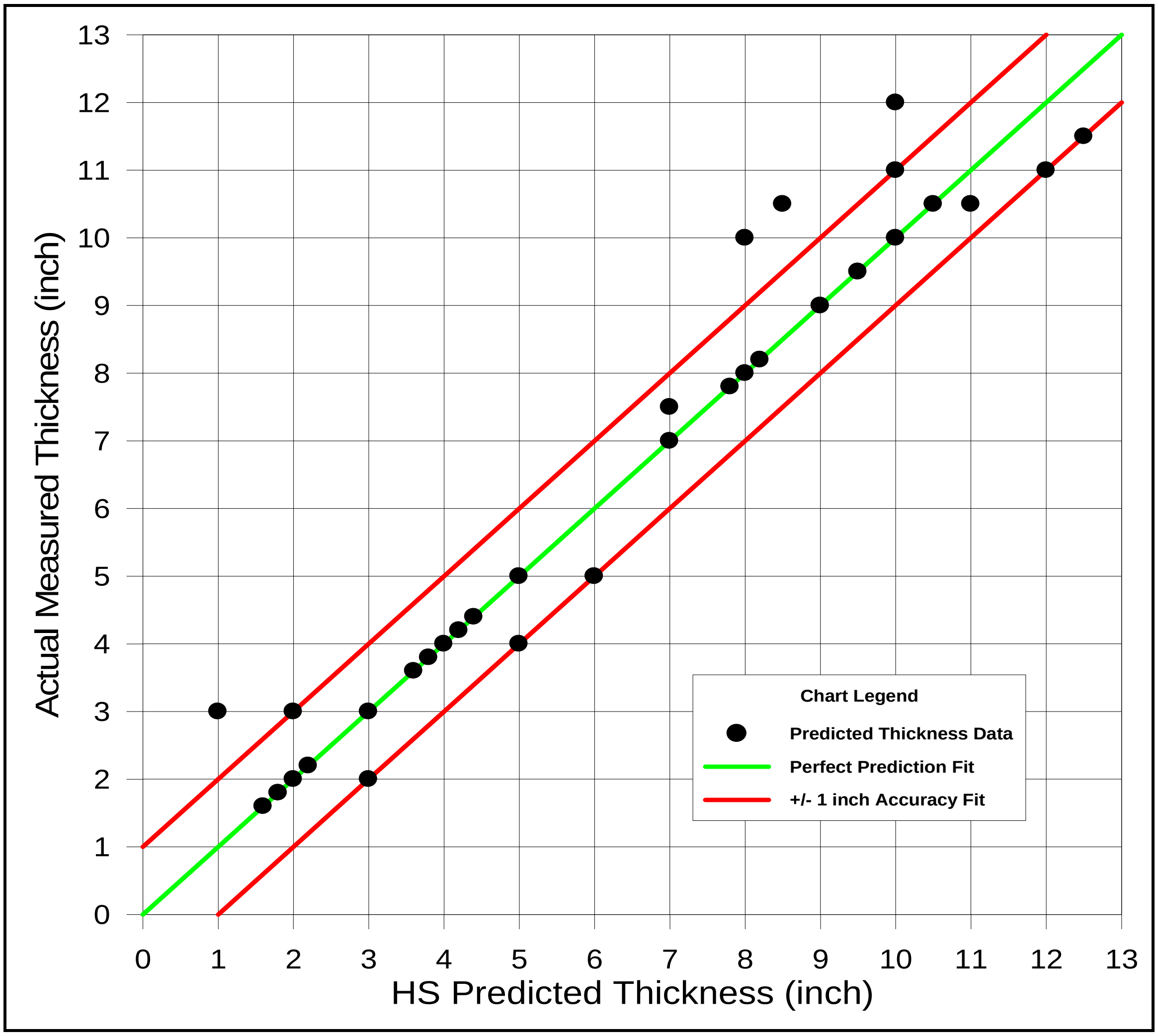


Figure 5.11. HS prediction accuracy plot for the Monterey verification tests

Mine height predictions were not plotted since there was very little variation from the actual height (±1 inch over an 8-foot span). Both height indicators (Total Height and Current Height) perform with high precision and good stability.

The mining machine at Monterey continued to use the complete Horizon Sensor system until early in 2003. At that time the cutter drums were replaced and the mine elected to continue with the head-positioning functions only, due to projected thinning of their seam and the probability that the mining height needed for machine clearance would exceed the seam thickness. This system has continued to be operational and has been fully commercial for more than 2 years. Monterey continues to make monthly lease payments for the HP-CM system.

5.2.3 Twentymile Coal: HS-CM Joy 12CM12

Installation of an HS-CM system on a Joy 12CM12 at Twentymile Coal Company occurred in March 2002. The total installation time was approximately 16 hours. Once underground, the system electronics were fully installed and initiated. The installed system is shown in Figure 5.12 while the miner was still in the surface shop at the mine.

The standard calibration method was also not conducive to the normal sumping cycle of the Twentymile CM operators, so a new technique was developed where the initial sump was near the rock and the CM was driven in as far as possible while logging data the entire cut cycle, even if it is at a single thickness value the entire time. This maintains a realistic coal/air condition while measuring, and ensures a more stable prediction later on. This is done on the roof and the floor while the operators are doing normal sump cycles. It is normal for them to "take the floor coal" first (HS logs a floor cut) then go in on top and "take the roof out" (HS logs roof cut). The drawback with this method is that it must be repeated many times to get enough variety to fill the bins needed and have a high data count.

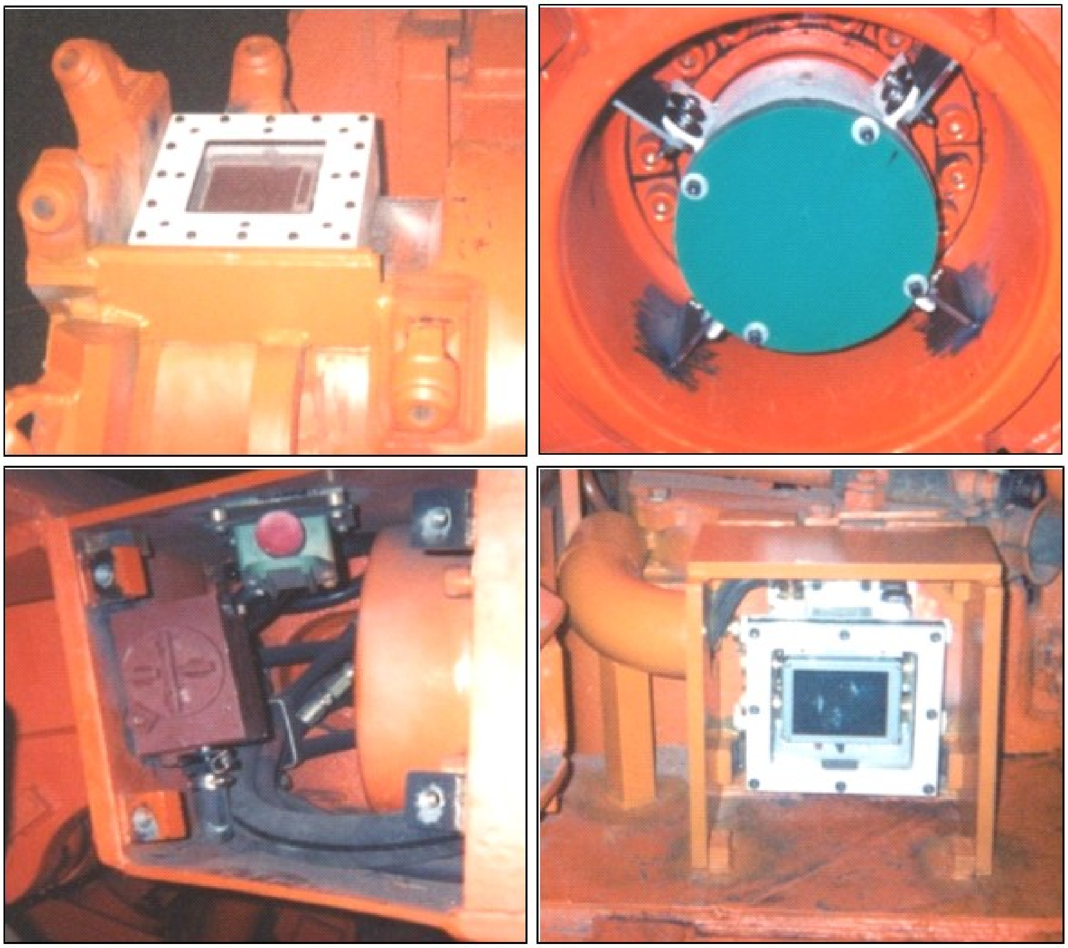


Figure 5.12. HS-CM system installed on a Joy 12CM-12 at Twentymile Coal Company: Horizon Sensor Unit (HSU) on the surface of the cutter drum (upper left); Horizon Power Unit (HPU) generator within the cutter drum (upper right); boom inclinometer in the cutter boom (lower left); and the GUI Display on the rear of the miner (lower right)

The HS-CM operational specifics for the Twentymile miner yielded a center frequency of 509.50 MHz (range= 3 MHz), an attenuation of 14 dB, and a window size of 10 degrees (5-point average). This final configuration yielded a test calibration curve suggesting very high antenna sensitivity, as seen in the test calibration curve in Figure 5.13. The system was then calibrated on the floor from 0 to 12 inches with the "max depth" at 8 inches, so that only 0 to 8 were predicted. The calibration was done specifically for the wet conditions in the down-slope entries. The system needed to be recalibrated once the water level went down along the entry slope.

The floor calibration was verified over the course of several cuts, and predictions from 0 to 6 inches seamed realistic (nothing thicker than 6 inches is ever cut). It was not possible to physically verify the predictions, but there was a correspondence between thickness prediction and the current height numbers. The coal-seam calibration numbers are shown in Figure 5.14.

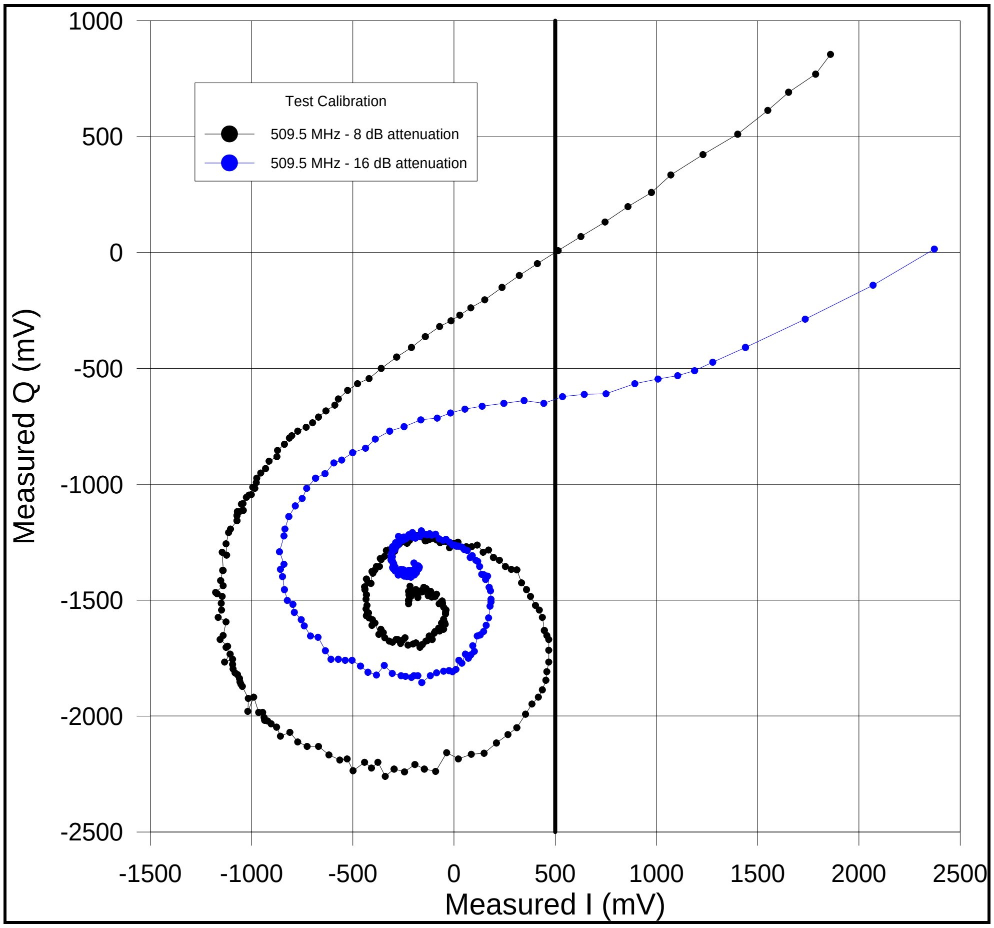


Figure 5.13. Twentymile Coal's HS-CM test calibration

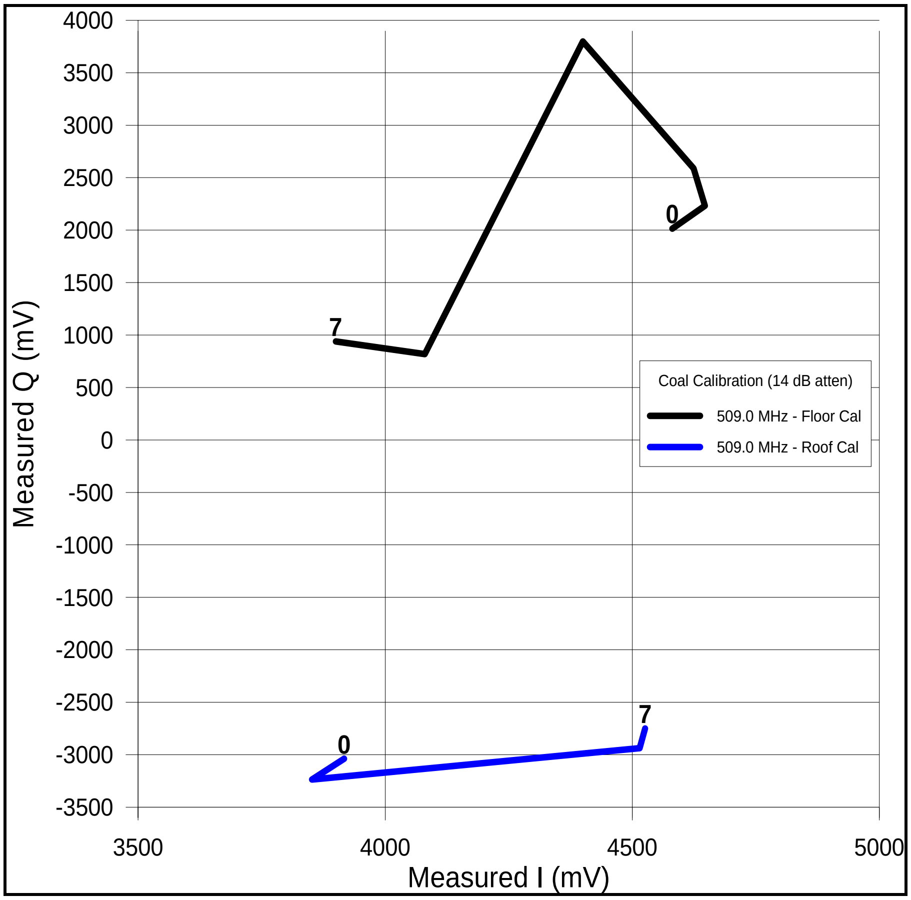


Figure 5.14. Twentymile Coal's HS-CM roof and floor calibrations

The response of the predictions was fairly quick. When sumping in 2 to 5 feet deep, there were usually one to four predictions that flashed to the screen (at an 800-mV sensitivity). These predictions did not stay on the screen after they were made, but rather cleared themselves after the coal was swept back into the pan. This was because the measurements from the resulting air gap were not related to the calibration table and a prediction could not be made.

While the system did exhibit satisfactory antenna sensitivity, the Twentymile HS-CM system could not be calibrated to satisfactory standards. The floor slope was too variable over the course of a single cut, and calibration values were systematically loaded into the wrong thickness bins (as dictated by the CBI). It was obvious that the system needed a body inclinometer to accurately input calibration bins and correct height measurements. It also needed boom inclinometer filtering to smooth the angle noise from the cutting vibration/impacts. These two tasks were directed back to engineering and the HS-CM system was left on the machine in a non-energized state. Only recently, Stolar returned to Twentymile and reinitiated interest in the program (the management and ownership of the mine had been in transition). Commercial agreements are being negotiated with the new parent company to revitalize the system with new components and begin the lease.

The physical assemblies themselves held up very well to mining condition, impact/abrasion, and use from personnel. These parts have seen 2 years of wear and are still functional.

With the exception of a display lens, no parts have needed to be replaced due to damage or wear. The total tonnage, shifts, and operational hours have not yet been documented.

5.2.4 FMC Trona: HS-BM Marietta Bore Miner

Installation of an HS-BM system on a Marietta Bore Miner at FMC's Trona operation in Wyoming also occurred in March 2002. The total installation took place underground in approximately 8 hours. The installation involved only the steel enclosures as the RAMP approval needed to install the system electronics was not yet granted.

The HS-BM system required the design and fabrication of an adaptor box onto which a standard HS-3 Sensor Enclosure could be mated to an HS-3 Battery enclosure. This sensor/battery combination would then need to be mounted on the trailing edge of one of the bore miner's cutter arms. The adaptor box for this application is shown in Figure 5.15. Once the adaptor box was shipped underground, it was welded in the appropriate location of the cutter arm. In addition to the cutter arm components, the Display Box and GUI Aerial Mount were installed on the machine. The installed system is shown in Figure 5.16 while the miner was at the underground face.

Following installation, the mechanical enclosures were monitored for clearance on the machine and any excessive wear or damage that might occur in normal mining operation. No problems were encountered in either clearance or abrasion. In the months following the wear testing, the RAMP approval was pending, so no electronics could be installed.

Recently, the MSHA approval was granted and the final software engineering is under way to customize the readout on the display screen to the customer's needs. While this system has not yet been fully initialized or calibrated, these tasks are pending. Only the commercial agreement has yet to be negotiated and approved; therefore, the HS-BM system is temporary idle.

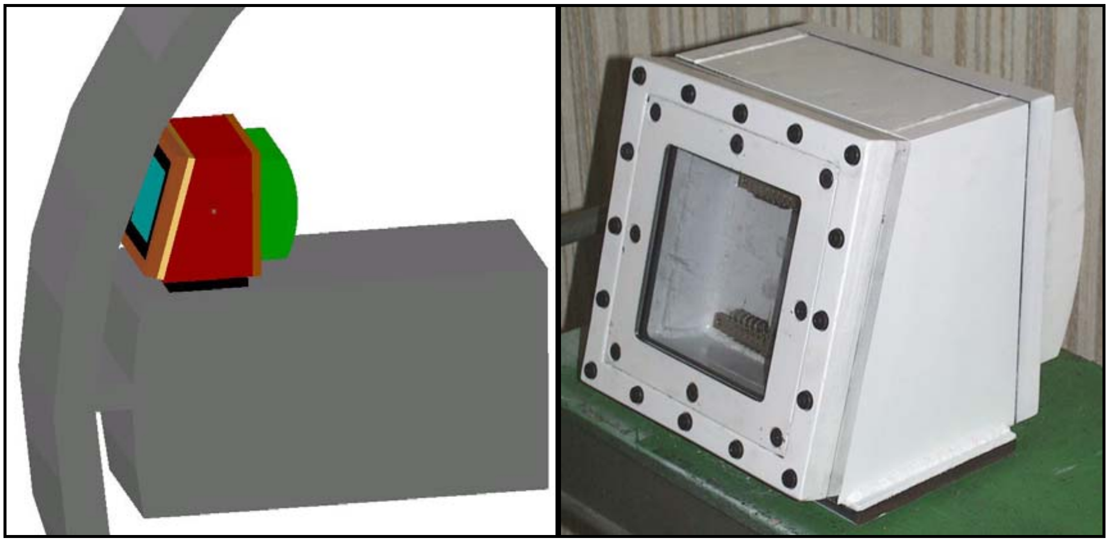


Figure 5.15. HS-BM adaptor box design and hardware for the bore miner cutter arm. The adaptor box is used to mount the HS-3 sensor and battery enclosures while protecting the interconnecting power cable.

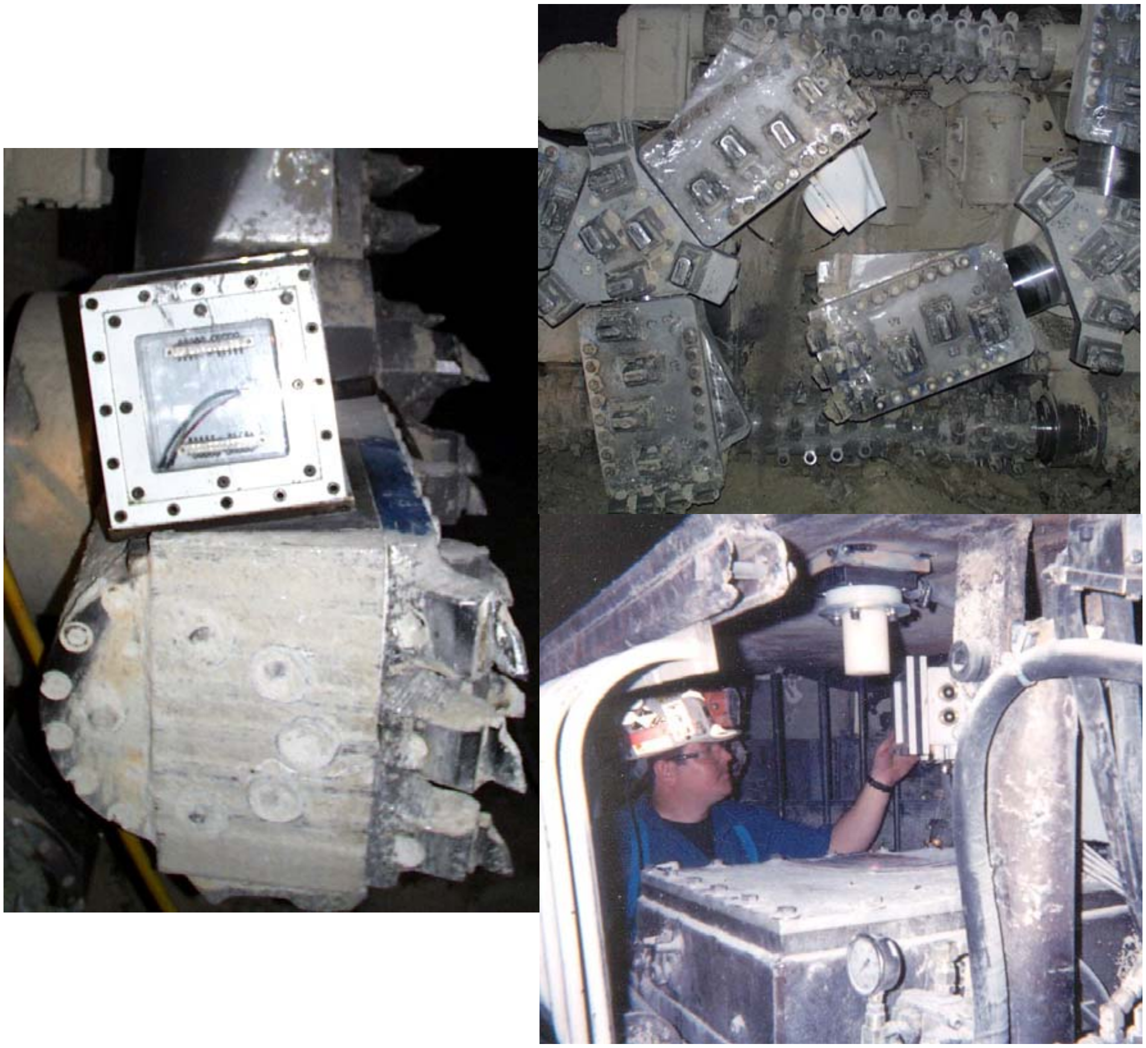


Figure 5.16. Installation of the HS-BM module enclosures on a Marietta Bore Miner at FMC Trona

5.2.5 Oxbow Mining Company: HS-CM Joy 12CM12

Stolar completed the installation of an HS-CM system (HS-3) on a Joy 12CM12 at Oxbow Mining's Elk Creek Mine on July 8, 2002.

Calibration of the HS-CM began on July 16, 2002, and included a program of tuning the sensor antenna element to the optimal geologic-dependent resonant frequency and impedance. This tuning process was followed up by a series of calibration steps in which the cutter head actively cuts coal while the sensor measures and records levels of antenna impedance through decreasing uncut coal thicknesses. The calibration process can require several hours due to the number of sensitivity and prediction parameters based on machine, geology, and operator-dependent variables, etc. However, this process time was reduced considerably as Stolar advanced the control software to include a greater degree of artificial intelligence.

Figure 5.17. Installation of the HS-CM on a Joy 12CM12 at Oxbow Mining Company

Oxbow's HS unit was calibrated during the swing shift on July 18, 2002. The calibration entailed storage of uncut coal data while actively sumping into the face at a desired height. This was done repeatedly for various heights. Following calibration, the system was predicting coal thickness accurately between 10 and 31 inches. Predictions above or below this range are possible, but the unit was calibrated for only the target range. For several shifts following calibration, the mine confirmed the calibration to be accurate (using bolted thickness).

Stolar and the mine then agreed that the system would be better used if the miner operators could cut as much coal as possible from the seam and then use HS to verify thickness while "trimming" the roof to the right height. Therefore, Stolar attempted to recalibrate the system on or around July 21, 2002, but variation in trimming style (amount trimmed, proximity to face or rib) made this technique impractical and too "operator dependent." This dependence led to each operator getting different results.

Stolar returned to the mine on July 24, 2002, to test the variations in the SUMP method versus the TRIM method. It was determined that the SUMP method would be more reliable and offer more accurate predictions regardless of who is operating the CM. A Stolar engineer then recalibrated the system using the original SUMP method and continued to work with the operators and instruct them on the nuances of the SUMP prediction.

Stolar returned to the mine on July 31 to investigate the system performance and found that predictions were as accurate and stable as they were the previous week. However, many operators were seen to reference the prediction screen at improper times in their sumping cycle, generally while trimming or free-spinning the cutter head below the roof (often with large air-gaps between the drum and the roof). Current software in the display head attempts to provide a prediction once per second, regardless of whether the head is spinning, cutting, or stationary. If the measurement used for prediction cannot originate from the geological calibration table, the display uses the nearest inclinometer-driven position to fill the gap. This creates variation in the prediction window and the operator must watch for any prediction that occurs during the end of a full sump-in, but before the coal clears away.

This convention of 1-second predictions under any time of drum rotation had been the root of prediction mistrust and operator misunderstanding. There was a fine window during which most roof sump-in cuts provided an accurate prediction. It was at this point that engineering changes were set in motion to eliminate any prediction that occurred when the head was (a) not rotating, (b) not actively cutting, and (c) outside a predetermined range. The primary objective at this point was to simplify the GUI screen and make the system more user-friendly. Working with the CM operators to obtain their comments was helpful for Stolar to achieve its objective.

During the July 31 visit to the CM section, Stolar observed the CM operator complete three cuts (20 feet in depth) in three different entries. During the cutting time, the predictions of uncut coal thickness for each full roof sump were recorded. These predictions were later compared to the bolter's verification of coal thickness using the auger drill. Predictions were made while using the SUMP method and the TRIM method. The purpose of recording predictions with both techniques was to compare the typical error seen by operators using one technique or another.

Records were also made of Total Entry Height as computed by the HS system and compared to hand-measured values. Tables 5.3 through 5.5 list the prediction values for these verification cuts.

Table 5.3. Verification data for Oxbow predictions in Entry 3, left cross-cut

Entry No.:	3	Operator:	Jesse Erickson
Location:	Left X-cut	Stolar :	Joe Duncan
		Date:	31-Jul-02
		Time:	15:30

Tube Side : Right

Bolter Verified Thickness	25			24	
Cut #		1	2	3	4
HS Predited Thickness (During Sump)		25	22	26	31
HS Predited Thickness (During Trim)		20	15	22	28
Mine Height HS		9' 11"		9' 8"	9' 11"
Mine Height Tape		9' 10"		9' 5"	9' 6"

Slab Side : Left

Bolter Verified Thickness	25				24	
Cut #		1	2	3	4	5
HS Predited Thickness (During Sump)		29	17	17	24	23
HS Predited Thickness (During Trim)		29	15	13		21
Mine Height HS						
Mine Height Tape						

Table 5.4. Verification data for Oxbow predictions in Entry 3, right cross-cut

Entry No.:	3	Operator:	Jesse Erickson
Location:	Rt X-cut	Stolar :	Joe Duncan
		Date:	31-Jul-02
		Time:	16:45

Tube Side : Left

Bolter Verified Thickness	30		36
Cut #		1	2
HS Predited Thickness (During Sump)		29	31
HS Predited Thickness (During Trim)		23	21
Mine Height HS			10' 4"
Mine Height Tape			10' 4"

Slab Side : Right

Bolter Verified Thickness	30				36
Cut #		1	2	3	4
HS Predited Thickness (During Sump)		24	24	26	29
HS Predited Thickness (During Trim)		21	21	10	
Mine Height HS				10' 4"	
Mine Height Tape				10' 3"	

Table 5.5. Verification data for Oxbow predictions in Entry 2, left cross-cut

Entry No.:	2		Operator:	Martin Aboyte			
Location:	Left X-cut		Stolar :	Joe Duncan			
			Date:	31-Jul-02			
			Time:	18:00			
Tube Side : Left							
Bolter Verified Thickness	13 in			14			12
Cut #		1	2	3	4	5	6
HS Predited Thickness (During Sump)		11	14	15	19	30	15
HS Predited Thickness (During Trim)		10	11	11	15	31	13
Mine Height HS							
Mine Height Tape							
Slab Side : Right							
Bolter Verified Thickness	13 in			11			8
Cut #		1	2	3	4	5	6
HS Predited Thickness (During Sump)		14	14	17	21	29	11
HS Predited Thickness (During Trim)		8	8	11		25	
Mine Height HS				10' 4"			9' 11"
Mine Height Tape				10' 3"			9' 11"

The following general statements of HS prediction accuracy could be made based on the calibration table in the sensor, as well as the user screen convention of displaying prediction numbers:

- Mine Height indicator tracks entry height accurately (±1 inch)
- Thickness predictions track head movement uniformly
- Actual prediction accuracy to date:
  - +2 inches for thickness less than 20 inches
  - ±3 inches for thickness between 20 and 30 inches
  - -6 inches for thickness more than 30 inches
  - Accuracy during SUMP Method is about 85%
  - Accuracy during TRIM Method is about 40%
- Occurrence of apparent system prediction failure 15% (could be due in part to rock spars in roof that reduce actual thickness in isolated areas).

The accuracy of the system, when used properly, is shown in Figure 18.

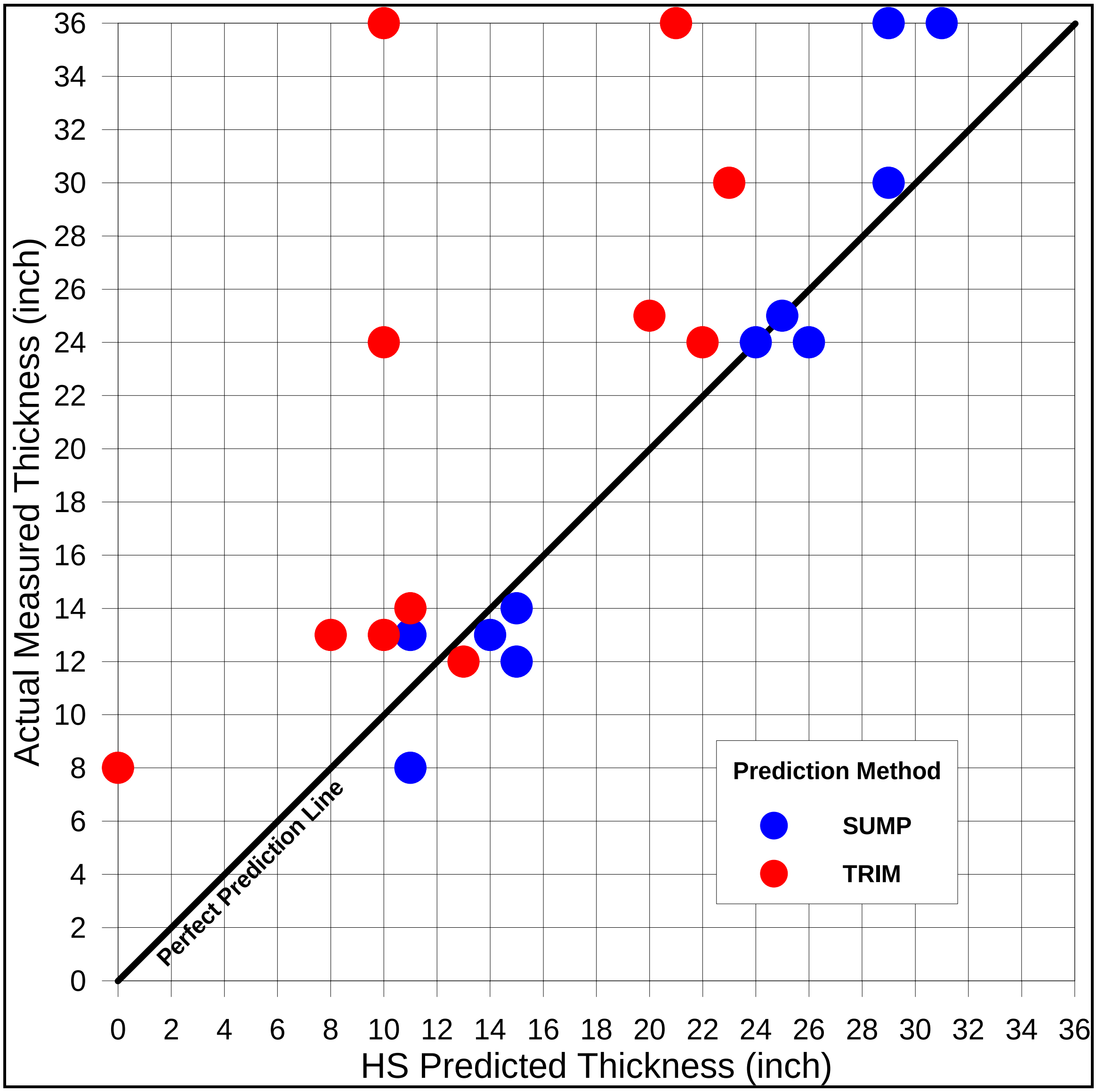


Figure 5.18. Prediction accuracy plot for HS-CM on Oxbow's 12CM12

When considering 20-plus hours of observed system response, mining condition, operator variance, display idiosyncrasies, and general prediction accuracy/stability, the following statements can be made:

- Operators had problems observing the screen at the proper time in the Sump Cycle. It was common to see the operator reference predictions during a trim cut or after he had begun to drop the head. It was also common for the operator to finish a cut and leave the head spinning freely under the roof and then look at the display after coal had evacuated.

- The operators were patient and receptive when being instructed how to identify “real” predictions from the noise, but there was room for improvement.

- Screen “noise” from a one-per-second prediction display was a problem and was the root cause of most operator misconceptions.

- Real failed predictions still occurred nearly 10% of the time regardless of operator miscues. Depth of penetration and geologic noise are still are the root of these errors.

- The system cannot see beyond 31 inches. When the thickness of roof coal was thicker than 31 inches, the system could only revert to a number near the last prediction—usually the high 20s to low 30s.

The replacement of the “one-per-second” prediction method in favor of a “cutting-only” method eliminated some random noise on the screen and gave the operator a better chance to make the right call. However, the “cutting-only” method was based on the use of accelerometers to detect excessively high G-forces on the head during the cutting process. While the system did exhibit satisfactory antenna sensitivity, the Oxbow HS-CM system could not be calibrated to satisfactory standards because of engineering problems with the accelerometer circuitry (for both triggering and cut-force sensing). This task was directed back to engineering the HS-CM system was left on the machine in a non-energized state. It was only recently that Stolar returned to Oxbow and reinitiated interest in the program. Commercial agreements are being negotiated to revitalize the system with new components and begin the lease.

The physical assemblies themselves held up very well to mining condition, impact/abrasion, and use from personnel. These parts have seen nearly 2 years of wear and are still functional.

5.2.6 Deserado Mine: HS-LW Joy 7LS Shearer

Installation of an HS-LW system on a Joy 7LS Shearer at Blue Mountain Energy’s Deserado Mine began in January 2003. The total installation time was approximately 10 hours; although nearly 10 more hours were spent fabricating and attaching the cutter drum counterweights (used to balance the weight of the sensor and battery enclosures on the shearer drum. The installed system, shown in Figures 5.19 and 5.20, proved rugged, dependable, and maintenance free during duration of testing.

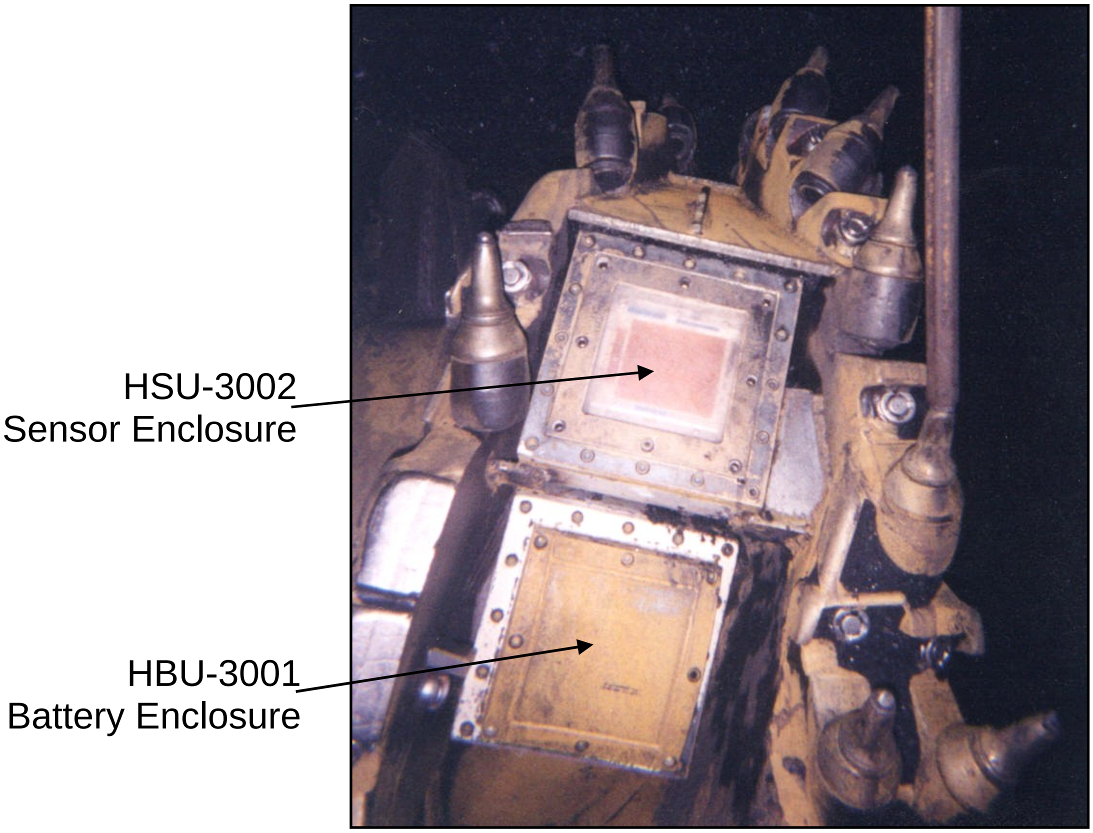


Figure 5.19. HS-LW system in operation on a Joy 7LS Longwall Shearer at the Deserado Mine. Shown here are the sensor enclosure and battery pack enclosure on the headgate drum.

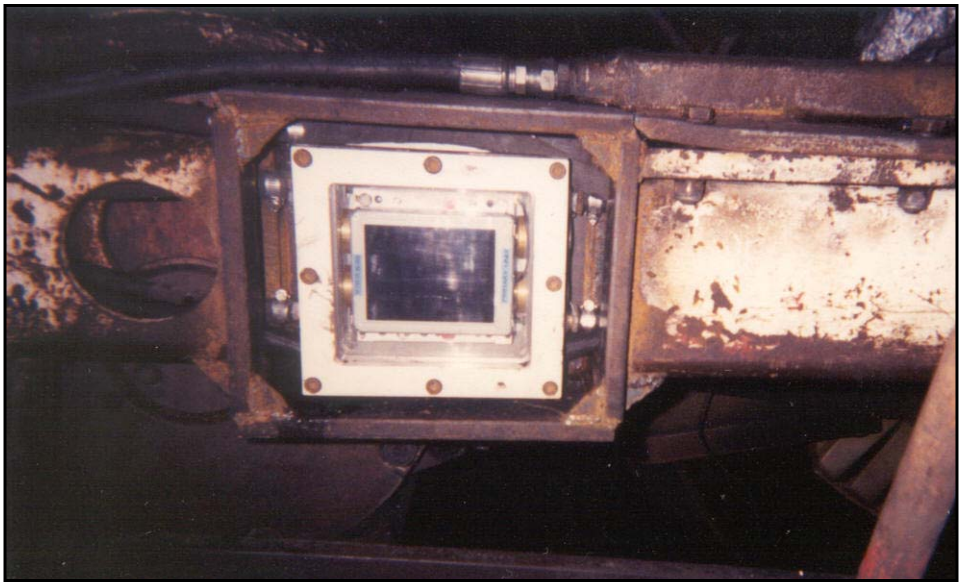


Figure 5.20. HS-LW GUI enclosure mounted on the water-boom arm of the headgate ranging arm of Deserado's 7LS shearer. The color LCD display is seen housed behind the polycarbonate lens of the enclosure.

Over the course of testing at Deserado, five major technical issues with the HS-LW system were realized that caused delays in the commissioning of the system. These problems were new to the HS program and had not been encountered during any other HS installations (which have primarily been continuous miners). Each of these problems has been corrected, or is in the process of being corrected. The unique nature of the longwall environment, as well as the type of machine being used, presented challenging issues for the technical team. The following is a list of these technical problems and their resulting solutions.

Problem 1: GUI Power Input Board. The machine power conversion in the controller box proved our first problem. The input AC voltage was lower (under full load) than originally anticipated. This probably resulted from the fact that the HS system shared the circuit with the JNA's existing inclinometer system. The lower AC voltage produced a DC control voltage for the HS GUIs that was insufficient. Therefore, the system would continuously reboot until a high enough voltage was supplied (usually when the shearer was inactive).

Solution 1: The power problem was resolved by replacing the transformer in the controller with one that would supply a higher output with the same input.

Problem 2: Measurement Trigger. The mechanism that sits Top-Dead-Center (TDC) on the sensor electronics during rotation had displayed signs of instability during the cutting action. This instability resulted from the increased centrifugal force the trigger switch (mercury ball type) sees during rotation and caused the TDC point to vary by as much as 30 degrees. This variability meant that the sensor did not always look straight up or down during measurement, but rather in many different directions. For obvious reasons, this had negative effects on the prediction mode. Prior HS programs used a trigger mounted at the center of rotation where there was not centrifugal acceleration (i.e., stable switch closure).

Solution 2: The trigger problem was resolved by replacing the mercury-ball switch with an accelerometer circuit that senses gravity changes during rotation (+ g-force after TDC and – g-force after BDC). The circuit was originally used as a cut-force sensor but was modified for cyclical triggering. This device provided nearly TDC triggering and also filtered out forces encountered during hard cutting events.

Problem 3: Modem Antenna. The portion of the HS patch antenna that transmits data away from the Sensor and over to the GUI had an interference problem on the larger cutter drums of the shearer. This interference created noise in the data stream, which the calibration table viewed as "anomalous readings," adversely affecting performance. In addition, it was determined that the antenna was tuned to improper impedance (50 ohms) and a higher impedance antenna should be installed (70 ohms).

Solution 3: A new type of antenna was designed that did not have the same type of interference problems as the original. It also had a higher impedance value which improved the signal to noise ratio. These modifications cleaned up the data stream and made predictions more stable. This solution required the sensor enclosure to be opened and modified.

Problem 4: Mine Height Indicator. The mine height numbers displayed to the screen had been erratic and/or erroneous. This occurred due to the inclinometers being improperly initialized when a cable had been damaged. A severed inclinometer cable in the body of the shearer was found and did not allow the head and tailgate drums to communicate, disabling the mine height capabilities. In addition, it was determined that excessive vibration in the controller created too much variation in the output of the body inclinometer. This caused erratic over-correction of the boom inclinometers by the body inclinometer.

Solution 4: The severed cable was replaced and the functionality restored. The noisy body inclinometer was easily corrected by the addition of a filtering capacitor to the GUI Input Power Board. Therefore, this problem was resolved by providing some maintenance time in the controller. This solution requires the controller enclosure to be opened and the filter added.

Problem 5: Battery Life Span: The original battery packs did not last a sufficient amount of time between replacements. This proved tedious and inconvenient for battery replacement. While this battery pack was always considered “temporary” because of its low capacity, there has still been a technical flaw in the pack.

Solution 5A: The technical flaw in the existing pack concerned the pack’s fuses. The battery pack was made up of three individual 18VDC sleeves (15 ampere-hour [Ahr] each) in parallel, which added up to a capacity of 45 AHr. However, each of these sleeves was fuse-protected before tying them together in parallel and if a fuse went out, the pack lost the contributions of that sleeve. Stolar found that many of the packs being removed from the Deserado shearer had full batteries but broken fuses (lower AHr capacity). It was determined that the “filament” type fuse being used was breaking during hard cutting action. This fuse type was replaced with solid-strip fuses that would not break under vibration/impact. This improved the life-span of the current battery pack.

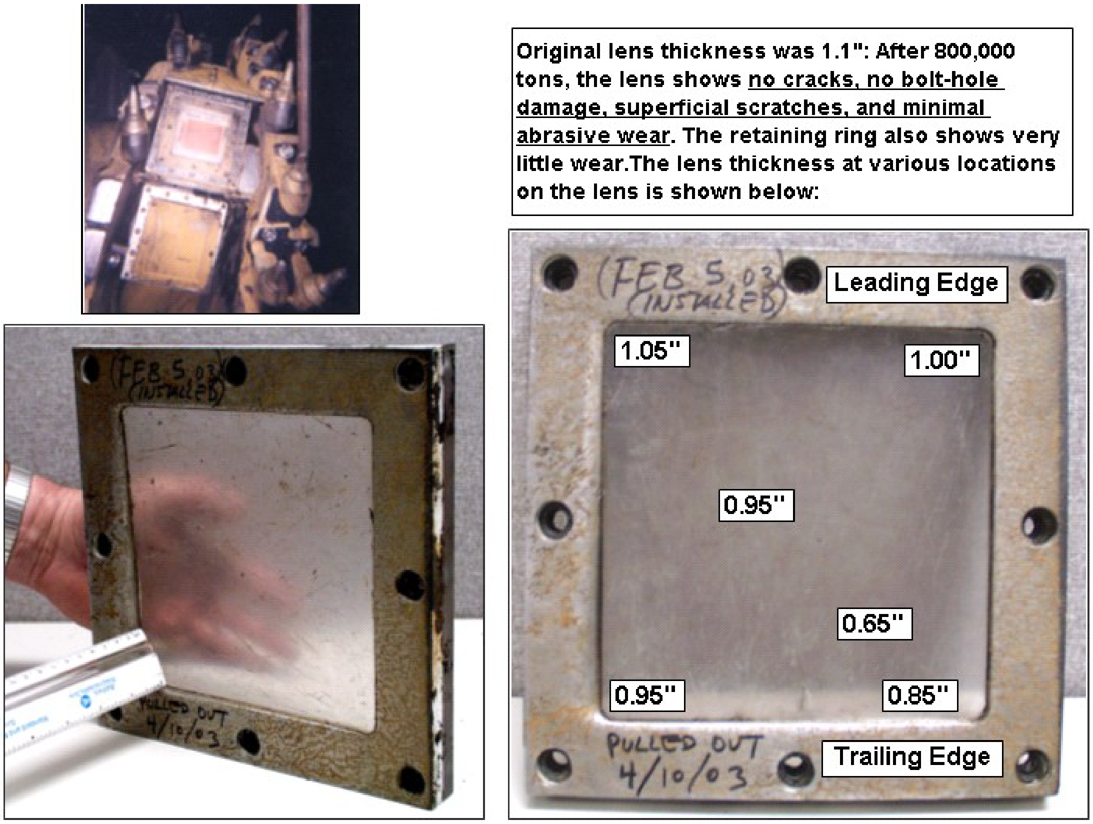
Solution 5B: A larger battery pack was nearing approval from MSHA. This new battery had four to five times more capacity than the original pack and was comprised of rechargeable cells.

Solution 5C: The power generator can still be considered an option, but some serious engineering is needed to assess the feasibility of installation on the existing drums.

Once each of these technical problems had been addressed, a focused effort was put into the initialization and calibration of the Deserado HS-LW. However, this effort ended in February 2003 when a Stolar technician was seriously injured by an advancing longwall shield while performing a calibration routine. Following an investigation by MSHA, Stolar, and Deserado, it was determined that the process of manual calibration on an active longwall face was too dangerous and safeguards were not in place to ensure that the HS calibration could be done without incident. This effectively ended the testing phase of the HS-LW system at Deserado. The calibration routine, both the process and software, needed to be modified so that operators could perform the steps on an active longwall face while being clear of advancing longwall shields.

The HS-LW system was left on the machine in a non-energized state. It was recently returned to Stolar and found to be in excellent condition (mechanically and electronically). A new commercial agreement is being negotiated with Blue Mountain Energy to revitalize the program at Deserado based on the success the HS-LW system has had at eastern US coal mines in the last year.

The sensor lens assemblies were found to have maintained their thickness even after several million tons of coal mined. Figure 5.21 shows the lens after only 2 months on the longwall face (over 800,000 tons). Rotating the lens assembly by 90 degrees every 2 months allows the lens to be worn evenly and extend its life span.



Original lens thickness was 1.1": After 800,000 tons, the lens shows no cracks, no bolt-hole damage, superficial scratches, and minimal abrasive wear. The retaining ring also shows very little wear.The lens thickness at various locations on the lens is shown below:

Figure 5.21.Abrasion and impact effects of the HS Sensor cover (polycarbonate lens and retaining ring) after 800,000 tons mined on the Deserado7LS Longwall Shearer over a 2-month period

The physical assemblies themselves were left on the machine for an extended period of time, giving Stolar a chance to monitor wear of the modules as a function of mined tonnage. These modules held up very well to mining condition, impact/abrasion, and use from personnel. These parts have seen more than a year of wear and are still functional.

5.2.7 West Elk Mine: HS-CM Joy 12CM12

Installation of an HS-CM system on a Joy 12CM12 at the West Elk Mine (Mountain Mining Company) was completed during March 2003. The total installation time was approximately 12 hours. In addition, several hours were spent welding boxes and brackets to the cutter drum during machine-shop rebuild. Once underground, the electronics were installed and the system initialized for use. As with all HS-CM systems to date, the West Elk system, shown in Figure 5.22, proved rugged, dependable, and maintenance free during duration of testing.

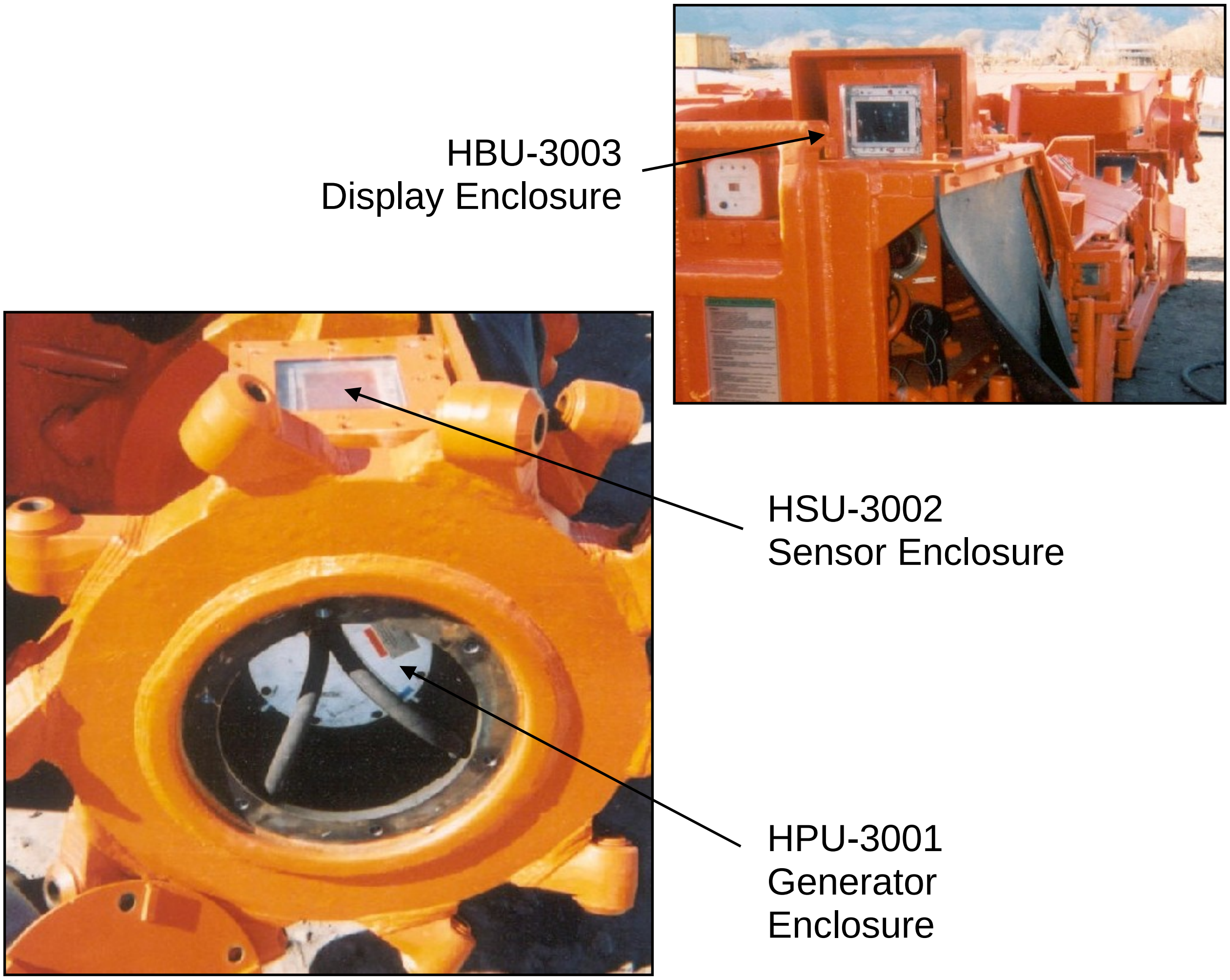


Figure 5.22. HS-CM system on the West Elk 12CM12 continuous miner prior to delivery of the machine to the underground face: HS GUI enclosure on the top-rear of the miner (top); sensor and generator modules on and within the cutter drum (bottom)

Once the machine was at the face, several days were spent calibrating the sensor and verifying the prediction accuracy. Mine height estimates were also scrutinized and both were found to perform will high precision and good stability. There have been several instrumentation failures in the year following commissioning. These include a generator failure (broken motor shaft), a damaged liquid crystal display (LCD) display (broken backlight tube), and a blown GPIB fuse resulting from a power surge.

The mining machine at West Elk continues to use the complete Horizon Sensor system and has been fully commercial for more than 1 year. West Elk continues to make monthly lease payments for the HS-CM system and the mine has hosted several prospective HS customers on behalf of Stolar, given access to the machine and testimonials on HS usage and documented benefits. West Elk is considered to be a real commercial success story for HS on a continuous mining machine. Additional HS systems have been ordered for upcoming mining machines at West Elk.

5.2.8 *Monterey Coal Company: HS-HP Joy 12CM12*

Installation of a HP-CM system on a Joy 12CM12 at the Monterey Coal Company was completed during September 2003. The total installation time was approximately 8 hours. This system included only the head-positioning components of the standard HS system (HGU, GPIB, and CBI). The installation was performed underground during a power-move maintenance window and no photographs are available. This system was installed on the second of two miners used at Monterey (the first also has an HP-CM system onboard).

After CBI initialization and verification tests were done showing high precision and good stability on mining height indicators, the system was fully commissioned as a commercial unit. This mining machine at Monterey continues to use the HP-CM system and has been fully commercial for 8 months. Monterey continues to make monthly lease payments for the HP-CM system.

5.2.9 *Massey Energy: HS-HW Superior SHM*

A new application for horizon sensing was investigated in 2003. The use of HS on a highwall miner had been planned early in the development of the product line, but it was not until October 2003 that a customer was found. Massey Energy agreed to lease a custom HS-CM unit for one of their highwall mining machines. This system, termed an HS-HW, was planned for installation on a Superior Highwall Mining machine (SHM) and Stolar worked closely with the OEM on the details of mechanical installation and electronic integration. A system diagram for the HS-HW is shown in Figure 5.23.

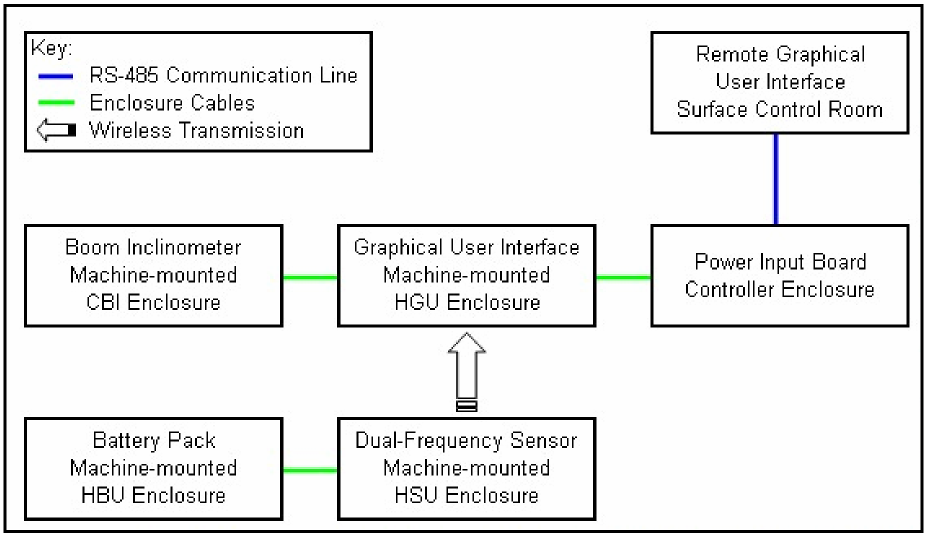


Figure 5.23. System diagram for the highwall miner version of the HS system (HS-HW)

While interfacing and certification issues were being worked out with the mine and the miner OEM, the Stolar engineering group redesigned several key modules from the HS product list for use on the SHM, and in some cases had to have MSHA certifications modified for this new enclosures. The HS-HW machine also needed a second display unit for use in the remotely located operator’s cab. This second display, termed the Horizon Graphics Remote (HGR), was fabricated specifically for the highwall miner. This HGR served as a satellite interface (RS-485 protocol) with the master HGU unit on the body of the mining machine itself, as shown in Figure 5.24. The master HGU was still needed as the main interface with the wireless data transmission for the sensor as well as the interface to the boom inclinometer.

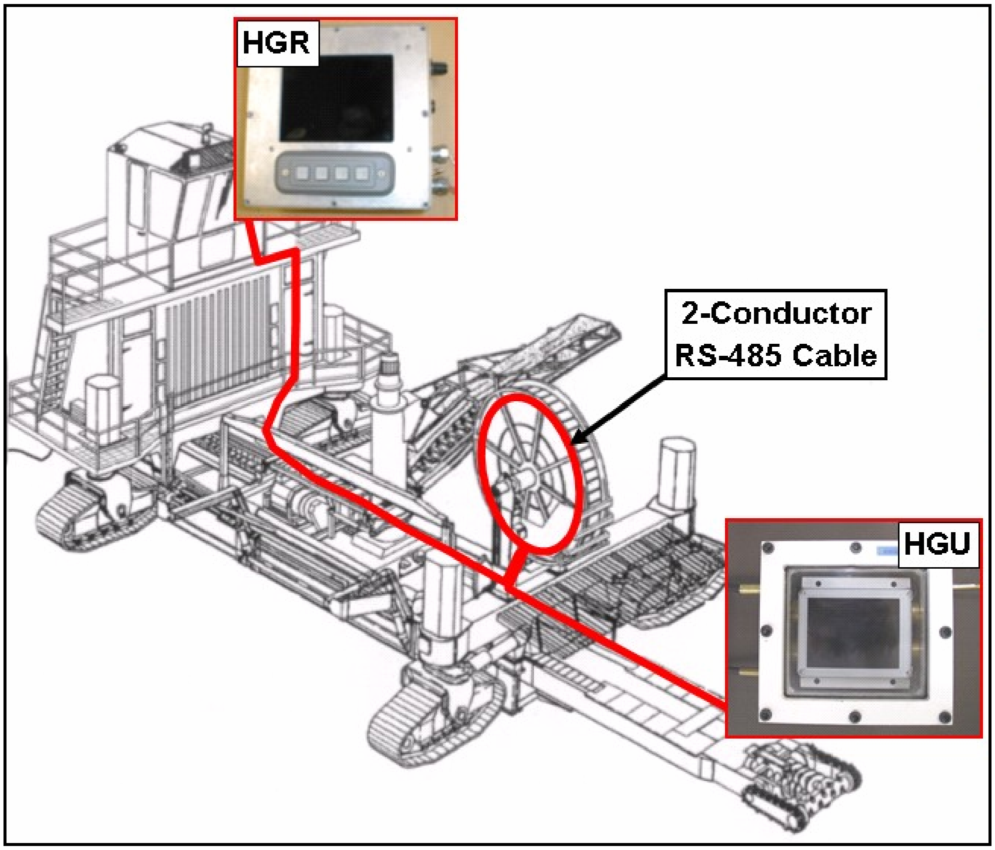


Figure 5.24. Locations of the two HS-HW display units on the Superior Highwall Mining machine. The display units communicated over a 1000-foot long cable run through the miner's retractable cable spool (with RS-485 protocol).

Installation of the HS-HW system on the SHM at Massey's Logan County Mine was completed in December 2003. The total installation time was approximately 20 hours. The majority of the system was installed on the miner while at the highwall face. Only the cutter drum components (sensor and battery pack) were installed at a machine shop after drum rebuilding.

A preliminary drum-battery combination was installed on an older cutter drum prior to complete system install just to check cutting effects. Since the mining machine head assembly was a low-seam drum with a small diameter (13 inches), there was concern that the sensor and battery boxes would even fit on the drum surface, let alone cut coal with no drag effects. Fortunately, the test drum proved that the presence of the sensor and batter enclosures, mounted in the center of the cutter drum, did not affect the cutting action or operation of the miner. This dummy head was run for more than a week before the rebuilt cutter drum was released for final HS installation work. The final cutter drum assembly is shown in Figure 5.25. The HGR display is shown mounted in the operators cab in Figure 5.26.

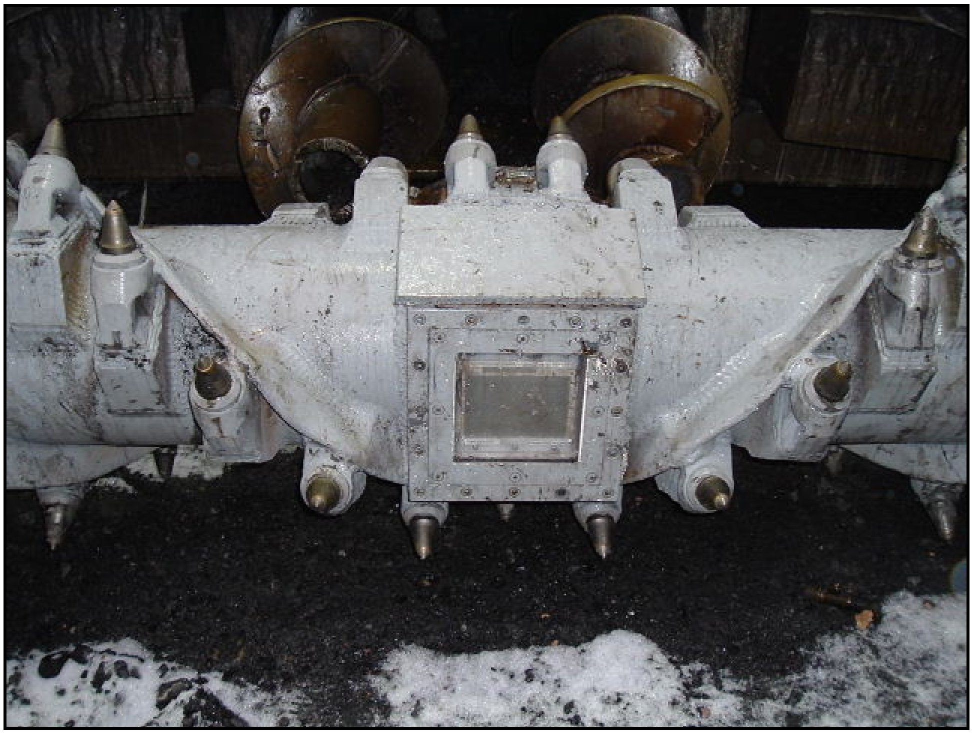


Figure 5.25. HSU sensor enclosure mounted on the SHM machine cutter drum. The HBU battery enclosure is fixed to the opposite side of the drum and the interconnecting power cable is shielded within a steel cover plate connecting the two enclosures.

Figure 5.26. View of the HS-HW Remote Graphic Unit mounted inside of the highwall miner's operator cab

5.2.10 Sufco Mining Company: HS-HS Joy 12CM12

Installation of a complete HS-CM system on a Joy 12CM12 at the SUFCO mine was completed during December 2003. The total installation time was approximately 16 hours. This system included the complete sensor and generator installation on the cutting drum as well as the display, inclinometers, and power board submodules. The installation was performed underground during power-move maintenance windows and only photographs of the machine prior to installation are available and shown in Figure 5.27 (from the rebuild shop taken during HS installation planning).

Figure 5.27. View of the SUFCO 12CM12 during rebuild. The photos here show the eventual mounting locations for the HS-CM display enclosure and sensor enclosure. The actual installation took place underground at SUFCO and no photos are available.

The full HS electronic assemblies were installed underground and the unit underwent several weeks of verification testing for prediction accuracy. SUFCO intended to use the HS system to monitor coal thickness up to 30 inches. This would not be possible with a standard HS antenna package, so an alternate low-frequency system was implemented.

In addition to reengineering of the RF components and RMPA, a new accelerometer circuit for TDC triggering was also need on the SUFCO unit. It was found that the G-forces created on the SUFCO miner were higher than in any other HS-CM application and that the existing accelerometer device had too high a noise threshold to accurately trigger once per rotation. This lead to the engineering and implementation of a more complex accelerometer circuit for the SUFCO machine. This new circuit design actually used two accelerometers in the generator assembly instead of a single accelerometer in the sensor enclosure. The dual accelerometer convention was used so that a differential method of triggering would give better stability between each long-period rotation (filtering out high-period vibration). The circuit was also moved from the sensor to the generator enclosures so that less centripetal force would be exerted on the device (lowering the noise floor).

After system initialization and verification tests were done with the newer components, the system was fully commissioned as a commercial unit. This mining machine at SUFCO continues to use the HS-CM system and has been fully commercial for 5 months. SUFCO continues to make monthly lease payments for the HS-CM system.

5.2.11 CONSOL Energy: HS-LW Joy 7LS Shearer

Installation of a complete HS-LW system on a Joy 7LS Longwall Shearer at CONSOL's Robinson Run Mine began in December 2003. The installation effort included mounting of the sensor and generator assemblies on the shearer's cutting drums in a rebuild shop. This marked the first time in five HS-LW installations that a generator was used for a longwall shearer application. The larger drums on this particular machine had the internal space necessary for the HPU generator, which provided internal power routed up out of a clearance hole in the drum and feed directly to the sensor enclosure; no battery enclosures were added to the drum.

The rest of the HS-LW system was installed at a CONSOL Energy maintenance shop prior to taking the shearer underground at Robinson Run. Installation of the electronics was performed underground during power-move maintenance windows and only photographs of the machine from the rebuild shops are available and shown in Figures 5.28 and 5.29.

After system initialization and verification tests were scheduled to take place after the New Year, in 2004. This HS-LW system is fully commercial and, once commissioned (following late-winter performance verification tests), CONSOL will make monthly lease payments and order additional HS systems for both CM and shearer applications. In particular, CONSOL is ready to move forward with an HS-CM program on a Voist Alpine ABM-14 continuous miner for its Enlow Fork Mine in Pennsylvania. There is also a second 7LS in rebuild which would receive an HS-LW system once the commissioning of the primary system is complete.

Figure 5.28. Installation of the HS-LW drum mounted component enclosures on a 7LS shearer drum. This tailgate drum, along with its companion headgate drum, was installed at the longwall of CONSOL's Robinson Run Mine.

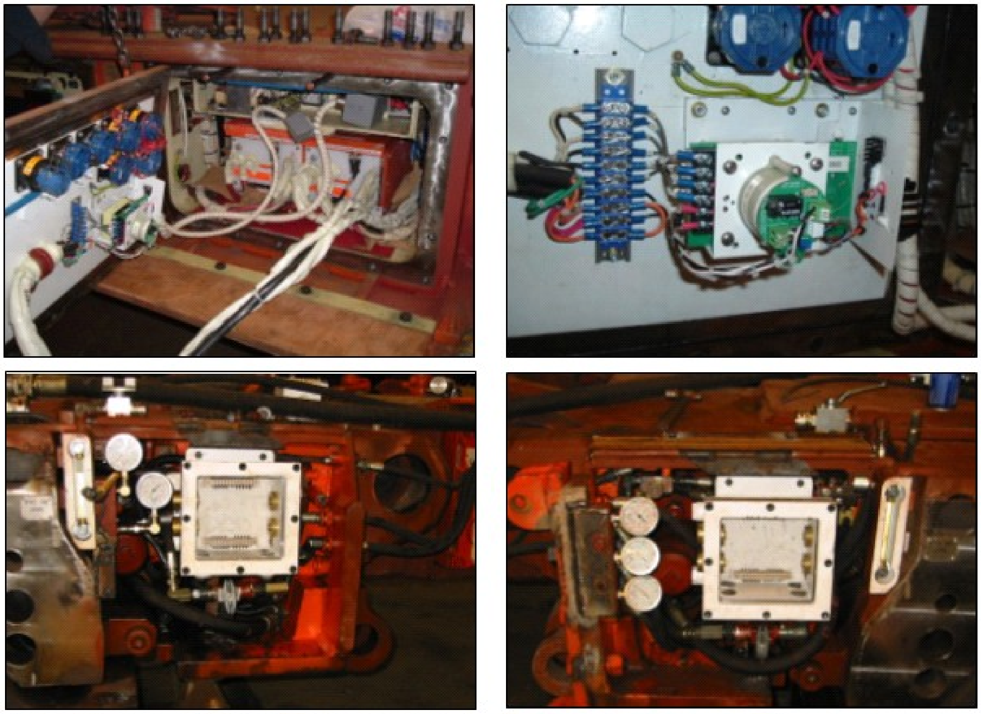


Figure 5.29. Installation of the HS-LW body mounted component enclosures and power board on the Robinson Run 7LS shearer drum.

5.3 Clean Coal Technology Demonstration Programs

The following sections outline funded HS-LW programs involving the demonstration of Horizon Sensor technology for the purpose of mining cleaner coal. These two programs took place in Illinois and Ohio and both involved HS-LW installations of Joy shearers (4LS and 7LS, respectively).

5.3.1 Monterey Coal Company (Exxon Mobil): Two Joy 4LS Longwall Shearers

This Clean Coal Technology (CCT) project is somewhat unique in that it was designed to demonstrate and confirm the benefits of the Horizon Sensor to improve the quality of run-of-mine (ROM) Illinois coal. Usually CCT projects address “downstream” technologies that remove pollutants in either the coal cleaning, coal combustion, or flue gas scrubbing processes. Stolar intends to verify that the application of HS in an “in-mine” CCT program can reduce the percentage of ash, possibly sulfur, and trace metals found in Illinois coal. Thus, the successful outcome of producing a cleaner Illinois coal supports the objective of the State’s Clean Coal Review Board (CCRB) to increase (or maintain) Illinois coal production.

Mounted directly on the coal cutter drum, the HS technology was shown to detect the coal and rock (roof and floor) interface, to enable the operators of the coal-cutting machine—in this case a longwall shearer—to cut either only the coal seam or the cleaner portion of the coal seam, leaving behind waste and dilution matter. The geological data examined in this project indicate that coal quality varies within the seam, and thus quality can be improved by selectively mining only the cleaner portions of the reserve referenced in inches from the roof or floor rock.

Stolar estimates that the HS technology has a significant benefit/cost ratio—a net $1 per ton. By cutting less rock and more coal during production shifts, the cost of producing a ton of ROM coal decreases. Producing a cleaner ROM coal can also reduce coal preparation costs, as well as improve the finished product. Finally, cleaner coal improves power plant efficiency (i.e., higher heat rate, less ash disposal, etc.) and thus a lower cost of electricity at the bus bar. Lower sulfur content of coal will reduce SO2 emissions and thus generate SO2 emission credits—another important economic benefit. Less ash in the coal means less waste to dispose of either at the coal preparation plant and/or the power plant. Today disposal costs well exceed $5 per ton; added benefits include less waste material that can leach into the ground.

Stolar teamed with Monterey Coal Company from the summer of 2002 until the fall of 2003 to install, operate, and evaluate the Horizon Sensor on two Joy 4LS longwall shearers. Prior to this project, Monterey management installed an HS unit on a Joy 12CM continuous miner for an initial “proof of concept.” Calibrated and commissioned in February 2002, the HS on the Joy 12CM successfully demonstrated that the HS unit could detect the coal seam-host rock interface. The application of the HS-LW for this CCT project has enabled the shearer operators of the shearing machine to better guide the cutting drum from a remote location, improving machine control and operator safety. The HS-LW systems, tested on both shearers, have shown that the technology can detect the proximity of the boundary rock through uncut coal. The sensor can provide the operator with mine height and coal thickness information so that adjustments can be made to the cutting profile. This report documents the entire scope and effort of the program and outlines the history of instrument deployment, data collection, system performance, and analysis of several key improvements in mining efficiency and mined coal quality once the Horizon Sensor was commissioned.

The Horizon Sensors, installed on the two longwall shearers, were calibrated and verified by Stolar field technicians, engineers, and Monterey management staff. The systems underwent multiple episodes of observation and documentation to determine that its prediction readings were accurate and to assure that the system could be used by the shearer operators. Verification involved logging predictions at specific shield numbers for floor coal thickness, and then digging the coal out to directly measure thickness. While several technical setbacks were encountered over the course of the program, the HS-LW system was improved continuously so that the function and performance of the system continued to be of benefit to the operators.

Operator and maintenance training was done as often as possible so that each operator had the ability to distinguish between the various readouts on the display and know what the implications of the measurements were. The operators were not trained to calibrate the system as this function was done when necessary by a Stolar technician. The operators were also supplied with reference cards to help understand the significance of particular readings.

Methods by which the team (Stolar and Monterey) measured or estimated the resulting "benefits" from HS usage were developed to monitor coal quality and reject rates before and after HS implementation. The mine worked with Stolar so that the proper variables could be documented and analyzed. These variables show marked improvement in production efficiency and coal quality (as a function of reject percentage).

Three total HS-LW systems were installed and used from July 2002 through August 2003 (two different longwall panels). Installation of the first HS-LW system on a Joy 4LS at Monterey was completed during August 2002. The total installation time was approximately 15 hours. A series of tests designed to verify system performance and accuracy were completed as of September 2002, while this machine neared the end of its use on Monterey's 7E/1N-ME longwall panel. This initial HS-LW system was comprised of a single drum-mounted sensor on the tailgate cutter drum. Tests were conducted on this HS-LW tailgate drum to demonstrate that indeed the technology could detect the coal-rock boundaries. The data and analysis of this initial test are presented below.

Installation of a second HS-LW system was completed on Monterey's new longwall shearer (also a Joy 4LS) as of October 2002. The total installation time was approximately 22 hours. This system used sensors on both the headgate and tailgate cutter drums. A series of tests designed to verify system performance and accuracy were planned for November and December 2002. However, due to a series of mechanical breakdowns on both the HS and the shearer itself, these tests were not completed. In early 2003, the system was prepared again for verification testing. In February, the mining conditions in the panel began to deteriorate and roof falls became a continuing problem. The shearing machine was used daily to cut large amounts of rock in the pan line. This not only prohibited calibration and testing work, but it also damaged the HS-LW system.

For example, in late February, the headgate sensor and battery pack were broken off the shearer drum while rock was cut. The team decided that testing would have to continue using a single-sensor system on the tailgate drum only. In the 6-month period between installation and testing, many instrumentation and damage-related issues were dealt with. The details of the issues, their repairs and modifications, and the final testing program are described in the following report. Stolar engineers made modification to the system to allow the single sensor to work independent of its partner. Active testing of the new unit began in April and continued into May 2003. These tests are discussed below. The system then continued to be used in mining operations on the 8E/1N-ME longwall panel until late in the summer of 2003. A monitoring procedure was put in place to document production benefits, quantify dilution reductions, and assess improvements in ROM coal quality.

The following series of photos (Figures 5.30 through 5.37) documents the installation process of the HS-LW system onto the Joy 4LS shearer to be used on Monterey's 8E/1N longwall panel. Stolar modified the shearer cutting drums by welding the Horizon Sensor Unit (HSU) enclosure onto the surface of each shearing drum. Electrical power required for the HS electronics is provided using a Horizon Battery Unit (HBU) enclosure welded on the surface of the drum. The Horizon Graphics Unit (HGU), which housed the user display and central computer, was welded to the ranging arms of each respective shearing drum. The CBI was bolted on the ranging arms. And finally, the Graphical User Interface (GUI) Power Input Board (GPIB) was installed within the controller box of each shearer and connected to the machine's AC power supply. MSHA approved all HS enclosures.

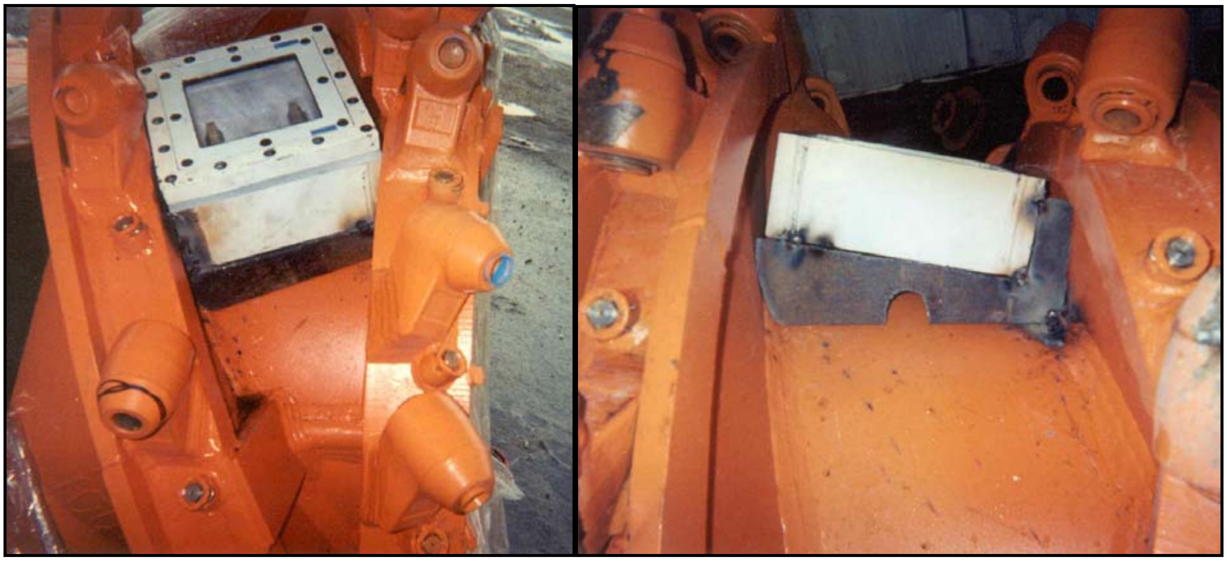


Figure 5.30. Installation of sensor (HSU) drop-box and support brackets

Figure 5.31. Installation of battery (HBU) drop-box and support brackets

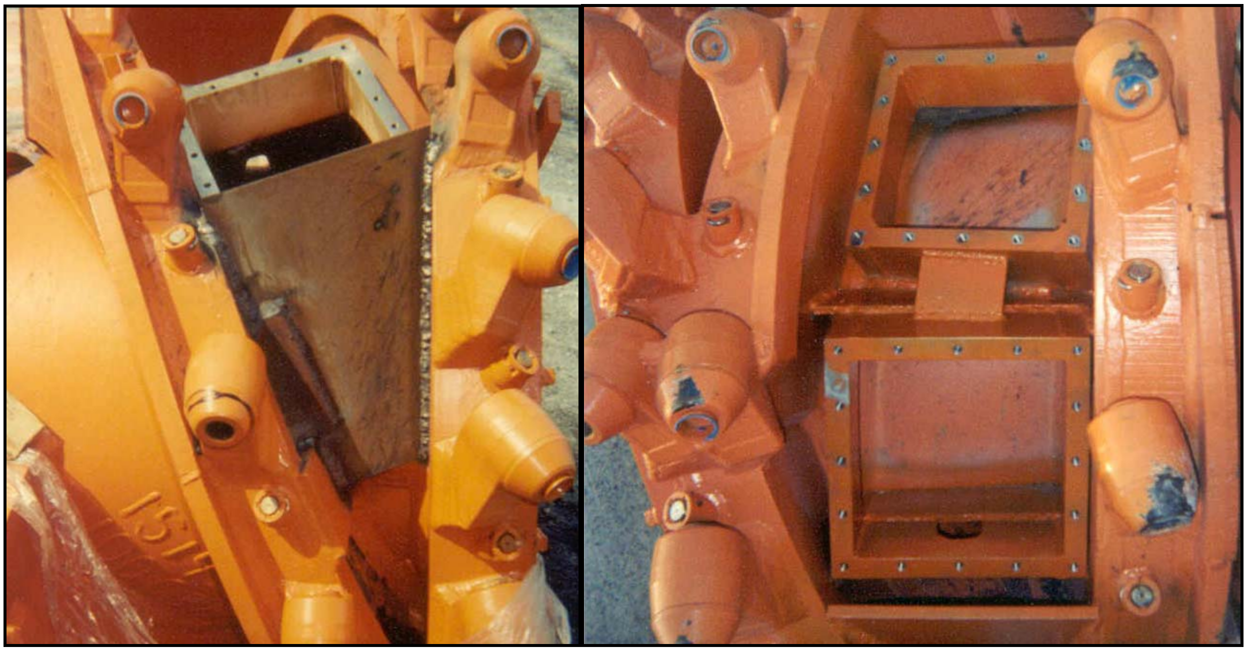


Figure 5.32. Abrasion/impact guard before the sensor and completed drop-box installation

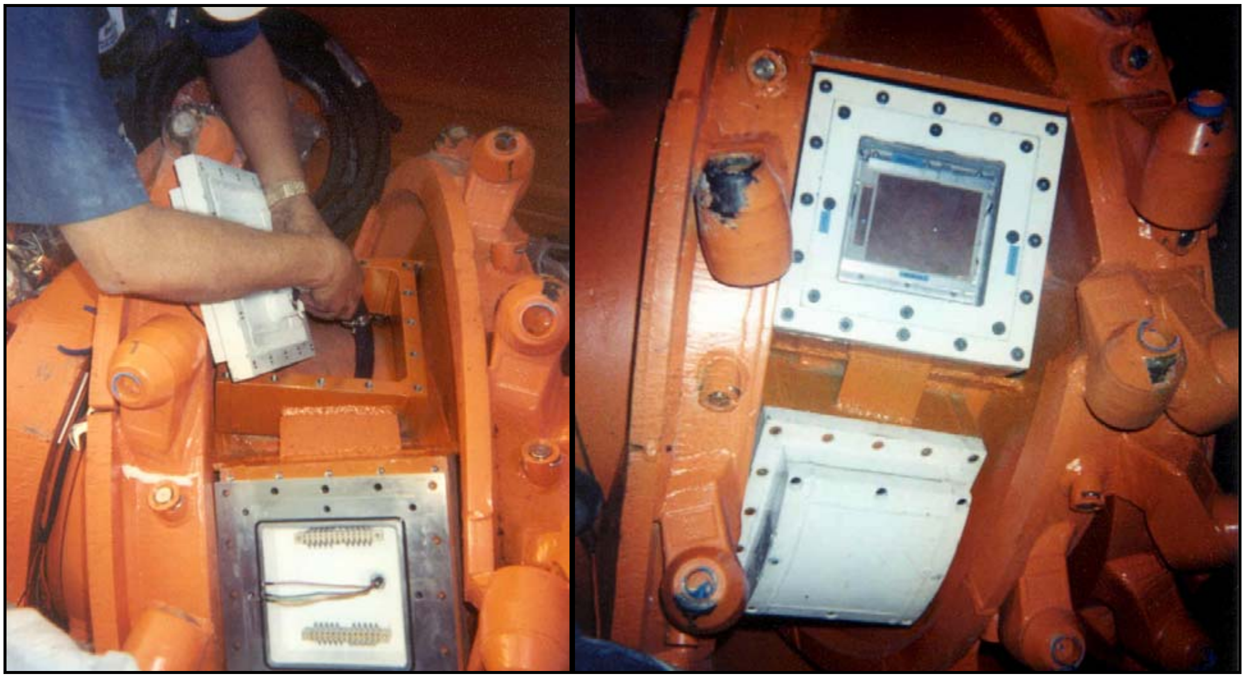


Figure 5.33. Component installation/wiring and completed final drum-system assembly

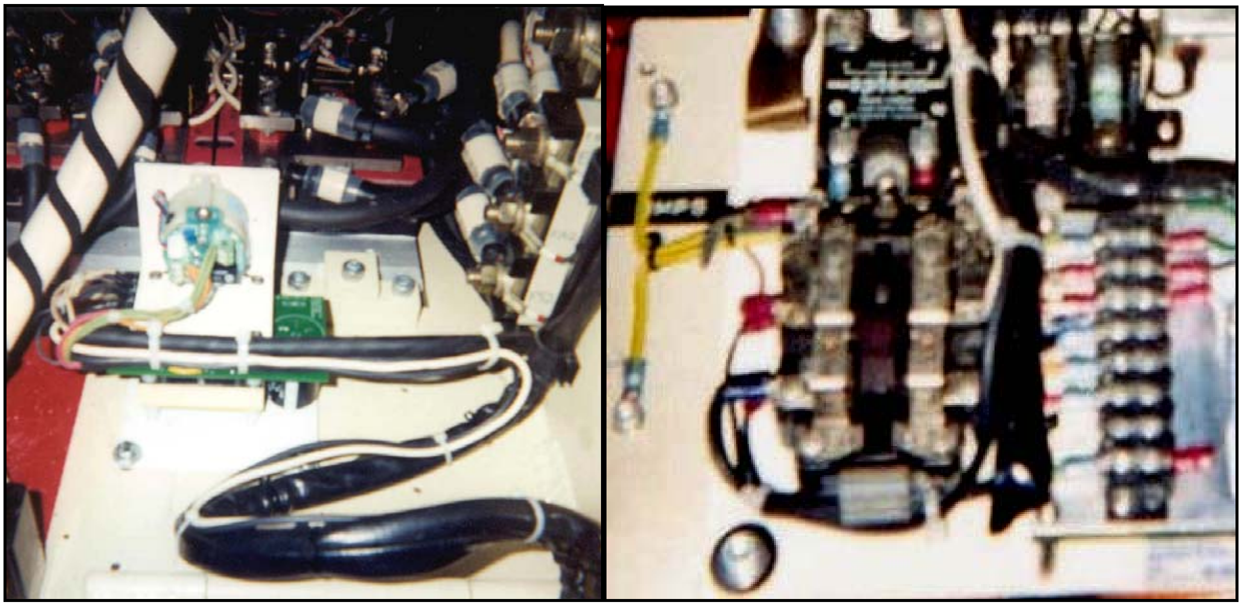


Figure 5.34. Installation of GPIB and AC voltage wiring on RC Relay (methanometer controlled)

Figure 5.35. Packing gland access panel on new shearer body (face side)

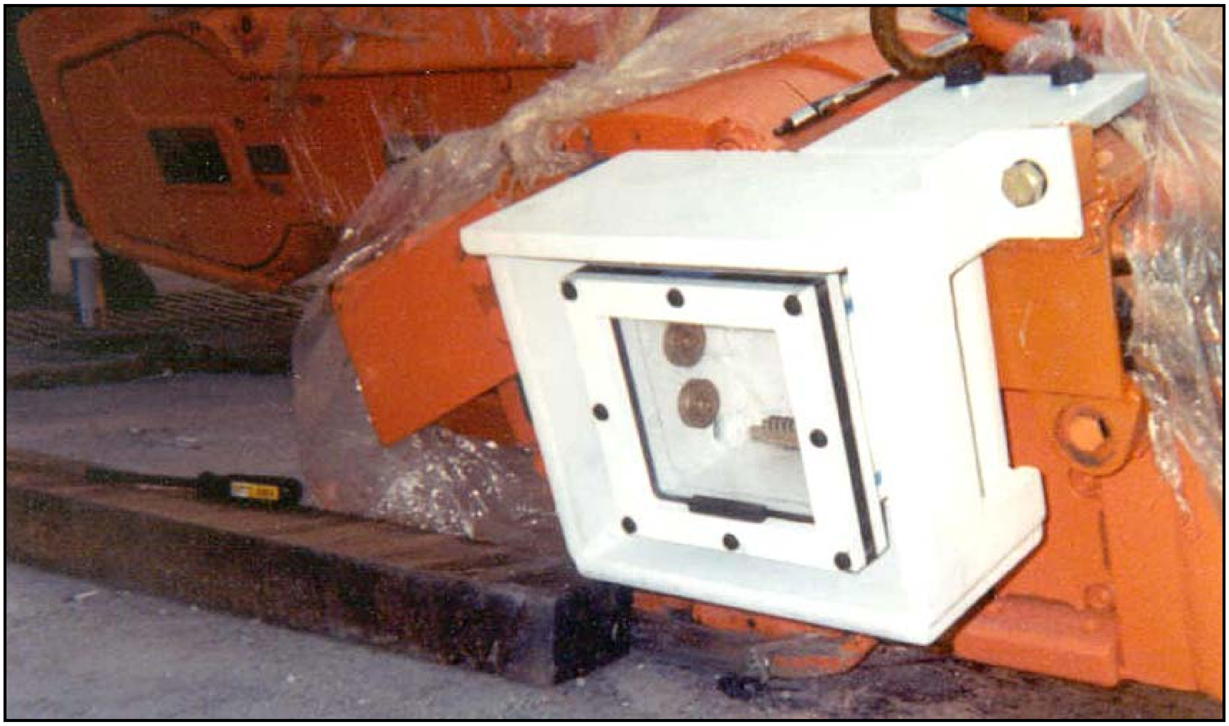


Figure 5.36. Installation of graphics display (HGU) and protection shroud on ranging arm

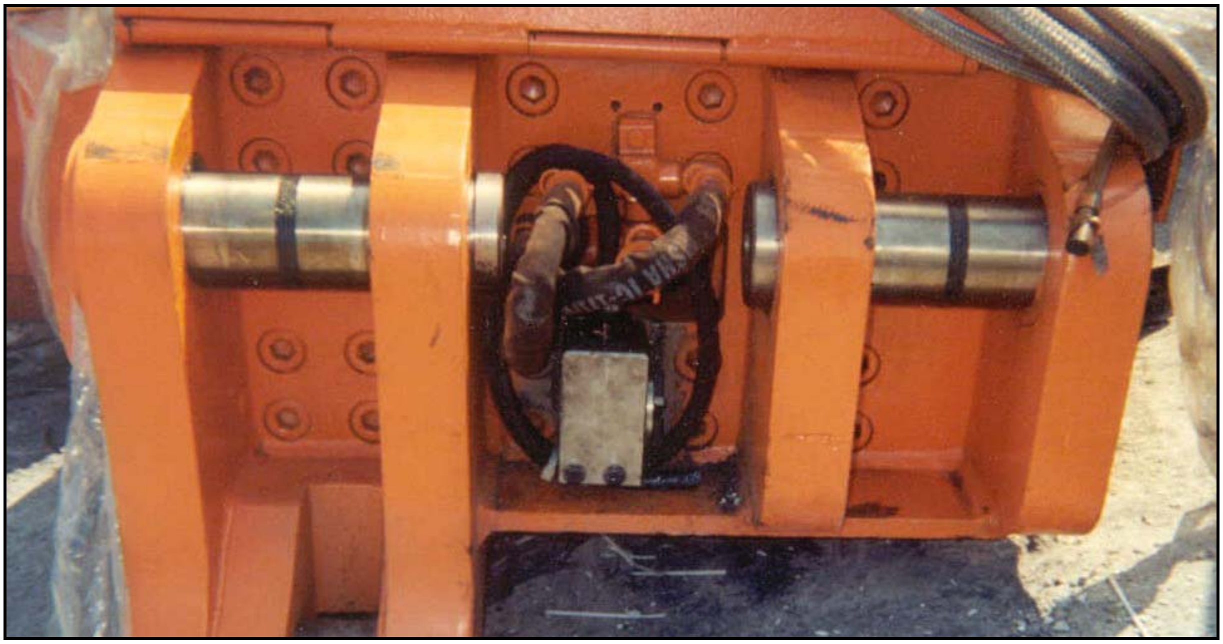
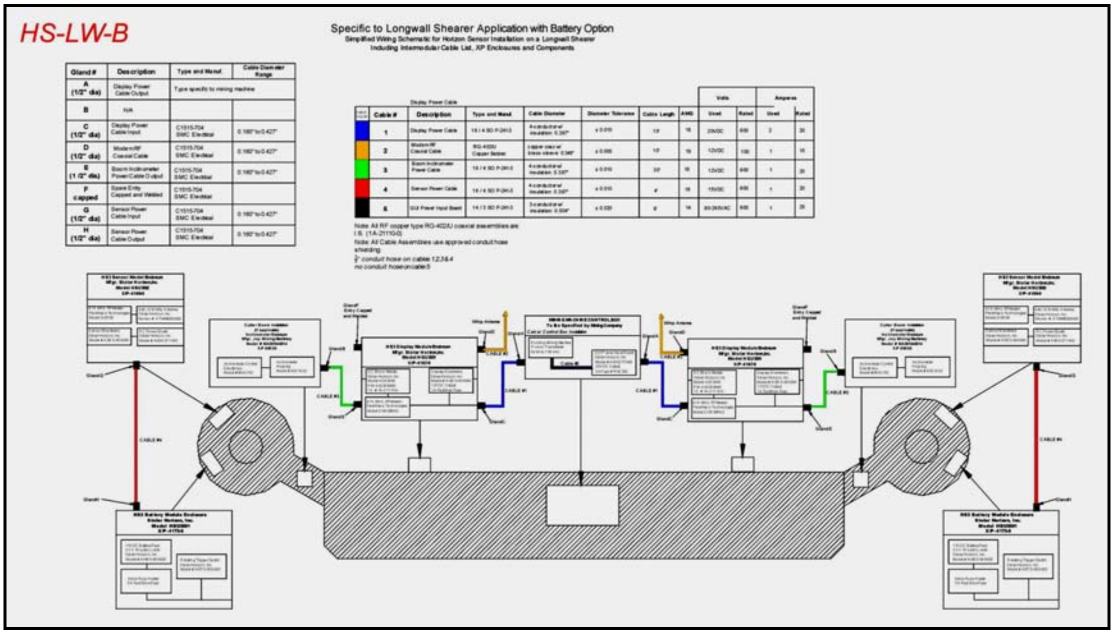


Figure 5.37. Joy inclinometer enclosure mounted on pivot end of ranging arm

The approval to install Stolar Horizon Control System on Monterey shearing machine LWS341E was accepted by MSHA on June 4, 2002 (Application #000306, Par #87935) and the approved system schematic is shown in Figure 5.38. Each time a system modification was required, the approval was modified in a RAMP process to maintain permissibility. The approval number for this shearer was SE-10033-1.



HS-LW-B

Specific to Longwall Shearer Application with Battery Option

Simplified Wiring Schematic for Horizon Sensor Installation on a Longwall Shearer
Including Intermodular Cable List, XP Enclosures and Components

Gland #	Description	Type and Manuf.	Cable Diameter Range
A (1/2" dia)	Display Power Cable Output	Type specific to mining machine	
B	N/A		
C (1/2" dia)	Display Power Cable Input	C1515-704 SMC Electrical	0.160" to 0.427"
D (1/2" dia)	Modem/RF Coaxial Cable	C1515-704 SMC Electrical	0.160" to 0.427"
E (1 /2" dia)	Boom Inclinometer Power Cable Output	C1515-704 SMC Electrical	0.160" to 0.427"
F capped	Spare Entry Capped and Welded	C1515-704 SMC Electrical	
G (1/2" dia)	Sensor Power Cable Input	C1515-704 SMC Electrical	0.160" to 0.427"
H (1/2" dia)	Sensor Power Cable Output	C1515-704 SMC Electrical	0.160" to 0.427"

Note: All RF copper type RG-402U coaxial assemblies are I.S. (1A-2110-0)
Note: All Cable Assemblies use approved conduit hose shielding
½" conduit hose on cables 1,2,3&4
no conduit hose on cable 5

Figure 5.38. System schematic for HS-LW with battery option

As expected during testing and evaluation at Monterey, several key Horizon Sensor instrumentation and operation issues came to light. Over the course of this program, seven technical issues have caused delays in the commissioning of the system. These problems are new to the HS program and have not been encountered during any other HS installations, which have primarily been on continuous miners. Each of these problems was corrected as quickly as possible. The unique nature of the longwall environment, as well as the type of machine being used, has presented challenging issues for Stolar's technical team, but resolution is complete.

The Horizon Sensor underwent many technical improvements over the course of the CCT program at Monterey. While some changes were required to solve design deficiencies, many were a direct result of moving from proving the technology in mining conditions to being a useful tool during normal coal production. The improvements include:

- Changing the Horizon Sensor (HS) software and hardware to reflect a Total Mine Height representative of position of both cutter heads on the shearer. This gives the operators real-time coal-face height as they mine.

- Capacitors have been installed on the outputs of the ranging arm inclinometers and the body inclinometer to filter out noise due to vibrations created during normal mining. This improved the stability of both the Current Height and Total Height for the operators.

- An accelerometer circuit has been installed in the Horizon Sensor as the TDC trigger. It replaces the mercury trigger and has improved TDC trigger stability by a factor of five.

- The Horizon Sensor Antenna Communication Patch and Signal Patch have been rotated 90 degrees with respect to one another. This eliminated communication interference with the sensor signal.

- The Horizon Sensor Signal Patch has gone from 50-ohm to 90-ohm impedance tuned in air. Once the antenna is installed and used in the coal cutting process, the 90-ohm impedance shifts toward 50 ohm due to the presence of coal rather than air; 50-ohm impedance is optimal for this system.

- A clock was added to the software that keeps track of Shearer Cutting Drum rotation time. This clock can be used to keep track of Horizon Sensor battery life and when a battery change is needed.

- A TDC trigger tracking function was also added to the software as a diagnostic tool. This function gives a running average of time between TDC triggers and the individual time elapsed between each TDC trigger.

When the headgate sensor and battery pack were broken off the drum, some modification was necessary to the drum-mounting boxes. The remaining mounting plates were secured and covered where possible and the headgate display was reinforced so it could continue to be used for head-position readings. The headgate sensor and battery pack actually suffered very little damage; the welds that secure the boxes failed. The boxes were recovered from the pan line and returned to Stolar. The tailgate drum was not damaged and visual inspection verified that the system was not in danger of being damaged.

Following several months of electronics upgrade and modification, several series of tests were conducted to verify performance on a modular and full-system level. The new accelerometer-controlled trigger was set up, and using the LED to indicate triggering position, the stability of the window was verified to be within 3 degrees of TDC even during cutting. A data average of 7 created a 10- to 12-degree window at TDC and BDC.

The Measurement Modes efficiently transitioned from Roof to Floor Modes when the cutter boom passed through mid-angle. The bounce was reduced to 2 inches since the Mine Height can be as low as 5 feet (average is around 6 feet) and the roof-to-floor transition must be rapid. Data transmission and command timing continue to be stable and dependable. The battery voltage output proved stable and reliable with no power loss on start-up (identifiable by modem LED fluctuation and/or trigger LED through lens assembly).

The inclinometer angle proved stable and reliable. The boom was initialized at the horizontal and the inclinometer was positioned within its enclosure so that its output was at a null (0 V out in the ±13-V range). GUI power reset timing was adequate. The GUI would reset itself during power trip, and flawless reboots were the norm. The machine's dimensional parameters (boom length, drum diameter, drum speed, and inclinometer scale) were measured and entered into the Setup menu exactly. The measurements provided nearly perfect boom height/distance computation; therefore, the predicted mine height was accurate to within 1 inch.

Resonant frequency and gain optimization were done once the HSU module was fully installed. The system functionality tests provided real-world proof that the system is performing as designed. Time was spent working on antenna sensitivity and resonant frequency during the Functional Testing phase. Water spray was dealt with in calibration, and at this point the water is not considered to be a problem. Coal-horizon-based calibration spirals are being catalogued, but visual inspection of calibration points implied a wide point-for-point variation (imperative for prediction stability).

During the calibration of this system for production, many critical parameters became apparent. These parameters affect the ability of the HS system to predict uncut coal thickness and provide stable and dependable output to the machine operator. The most critical parameters of calibration/prediction include:

- The shearer must be moving at its normal coal cutting speed. This ensures that the cutter drum has a constant density of cut coal in the vein and passes over the sensor antenna.

- The cutter drum must be fully engaged in the seam: full up during roof cutting and full down during floor cutting. This minimizes the air gap between the bit circle and the coal/air interface.

- The water sprays must be on and functioning properly. This ensures that the effect of the water spray on the antenna is constant and uniform, which allows it to be calibrated into the radio measurements.

- To properly calibrate the floor, the coal/rock boundary must be within ±3 inches of the bottom of the pan. This is critical because the proximity of the pan line with relation to the sensor element can and does affect the HS signal.

All of these parameters are important variables when calibrating, as any one of them can affect the HS signal.

During this program, two major episodes of system commissioning took place. This commissioning involved calibrating a new set of instrumentation for the machine and seam geology in place. These episodes generally involved several days of underground calibration efforts followed by weeks of observation and verification of HS predictions. The episodes took place in September 2002 on the first longwall shearer in panel 7E/1N and in May 2003 on the second shearer in panel 8E/1N. There was a 6-month delay between November and April during which instrumentation issues were resolved and several damaged components were repaired or replaced.

Prior to the first episode of verification tests, a series of calibration exercises took place to establish the optimal sensor setting on the machine. The resulting calibration curves for the roof and floor are shown in Figures 5.39 and 5.40, respectively. These calibration curves show a spiral continuity of RF measurements versus coal thicknesses ranging from 0 to 4 inches. Each of the coordinate-based measurements is unique to the coal thickness from which the data was sampled. These curves allow prediction accuracy to within 1 inch (±).

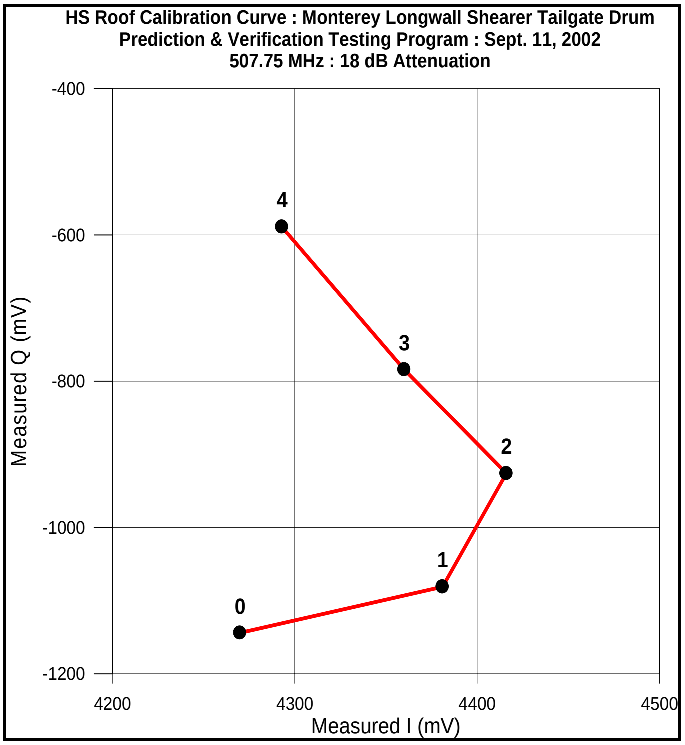


Figure 5.39. HS-LW calibration curves for the roof cut on longwall panel 7E/1N during system testing on September 11, 2002, at Monterey Coal Company

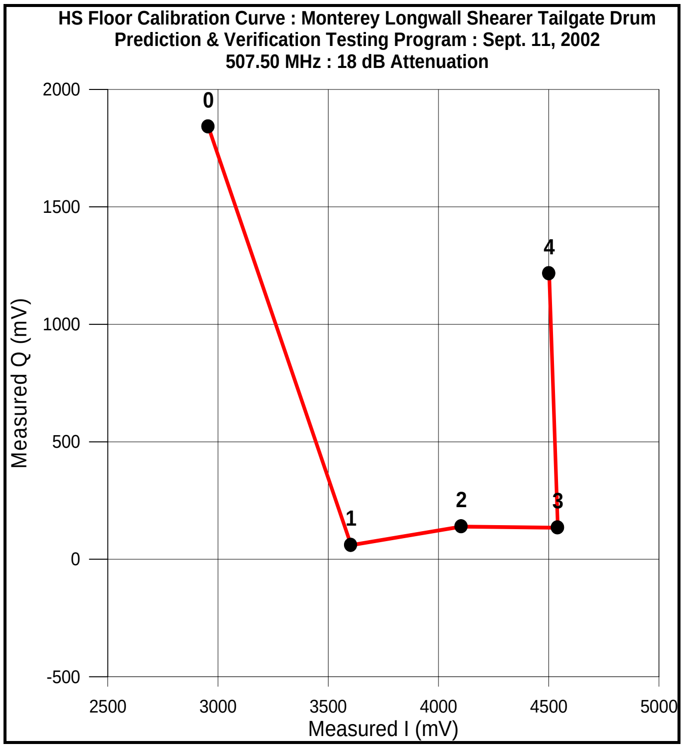


Figure 5.40. HS-LW calibration curves for the floor cut on longwall panel 7E/1N during system testing on September 11, 2002, at Monterey Coal Company

To test the prediction capabilities of the HS-LW system, a series of coal-cutting tests was designed that would allow uncut coal to be left in the roof or floor while logging thickness predictions over these areas. The actual thickness of the roof and floor coal could then be measured visually (roof) or directly (floor) for comparison to predicted values. These tests were carried out in a section of the longwall panel that possessed only 5- to 6-foot coal thickness.

Five total cuts were performed using the test plan described above: three (3) uncut roof coal sections and two uncut floor coal sections. The data gathered were used to correlate predicted coal thickness versus actual thickness. The actual coal thickness, as well as mine height, is judged by averaging the section being measured. The exact position of a planar boundary in the seam is often difficult to delineate due to irregularities in the cut (scoured) surface.

The predicted and actual thickness values shown in these figures can be combined into a single "accuracy" plot that compares the values along a line of "perfect prediction." This accuracy plot is shown in Figure 5.41. The roof data points are shown as red dots and the floor data in blue dots. The green region running diagonally down the plot is the ±1-inch region where the HS-LW system exhibits the majority of its predictions.

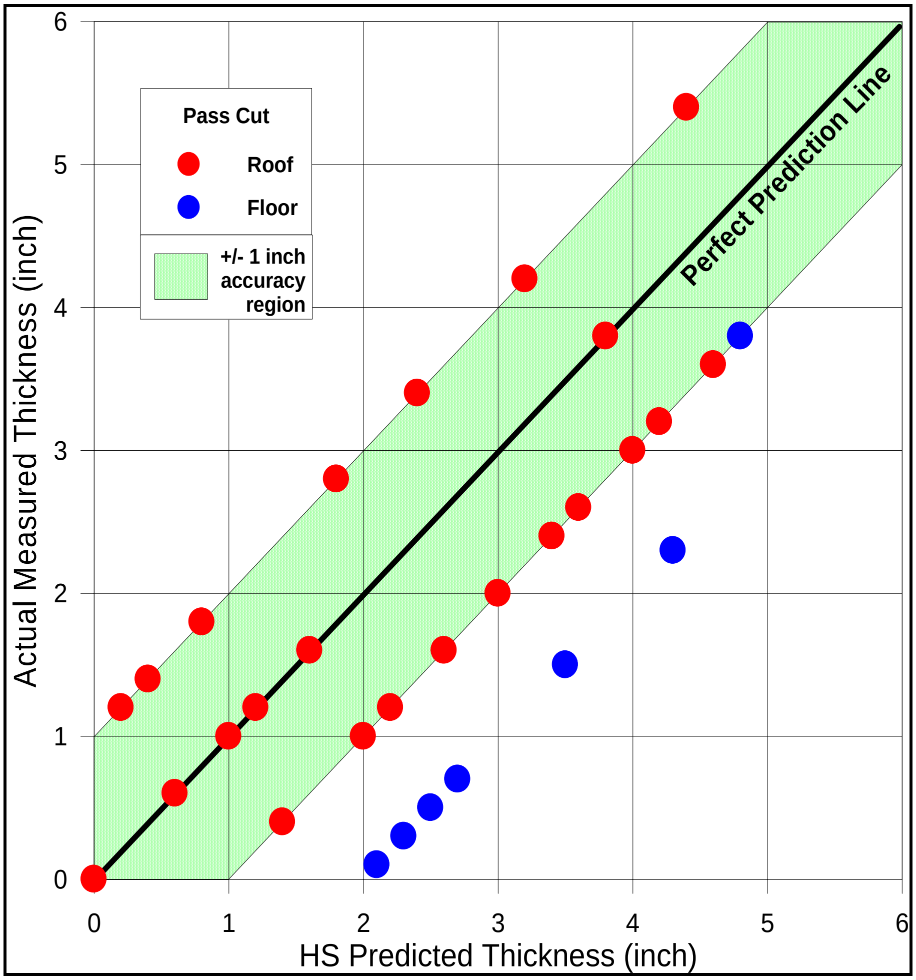


Figure 5.41. Accuracy plot for the floor and roof predictions during verification tests on panel 7E/1N

Even with the practical difficulty in physically measuring the actual coal thickness, the predicted values for the roof were within the ±1-inch range. This is better than the accuracy seen with the HS-CM system in the same mine. At first glance, the floor predictions appear to be consistently off by 2 inches, however, the fact that the predictions consistently overestimated thickness by those 2 inches implies that the floor's base level was simply initialized 2 inches high during the calibration sequence (a common thing to do when you cannot visually see the floor rock during calibration). Therefore, the accuracy at which the HS-LW system resolved the floor position relative to itself was actually near to perfect. A simple reinitialization of the floor's base level within the calibration table will shift these points back down to the actual level.

The excellent results of these measurements on the initial trial provided the team management with confirming data to move forward with the installation of the HS-LW on the second Joy 4LS on Monterey Panel 8E/1N. As indicated above, as a result of the loss of headgate sensor and battery enclosures, the tailgate system became the area of focus. Also, the critical calibration for Monterey was the floor calibration. Using the floor calibration method, the floor cuts produced calibration tables that adequately predicted coal thickness once the system was in the main prediction mode. The calibration curve for the floor is shown in Figure 5.42.

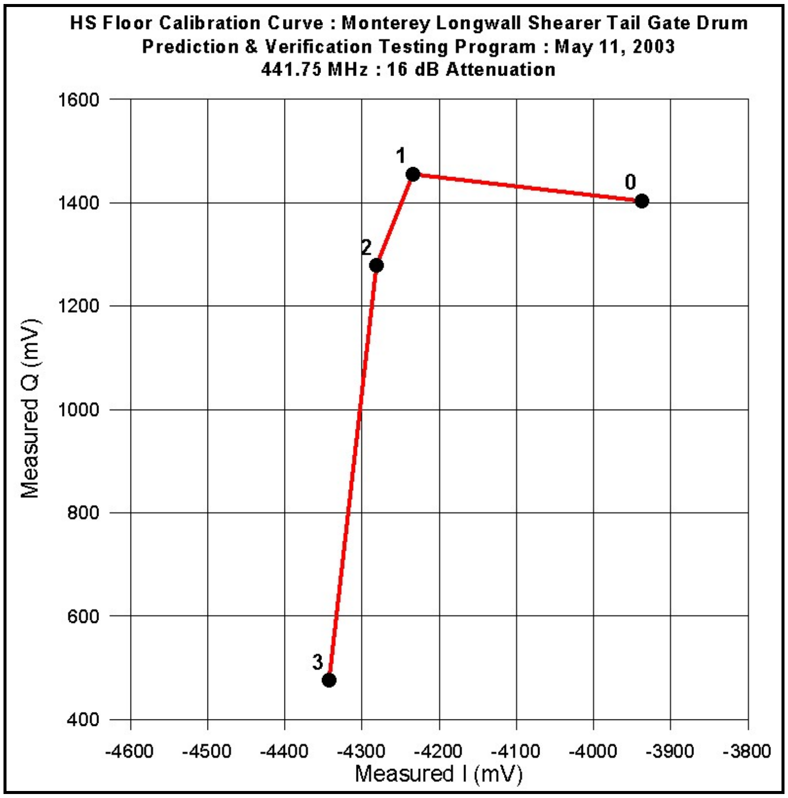


Figure 5.42. HS-LW calibration curves for the floor cut on longwall panel 8E/1N during system testing on May 11, 2003, at Monterey Coal Company

These calibration curves show a spiral continuity of RF measurements versus coal thicknesses ranging from 0 to 3 inches. Each of the coordinate-based measurements is unique to the coal thickness from which the data were sampled. These curves allow prediction accuracy to within 1 inch (±).

To test the prediction capabilities of the HS-LW system, a second series of coal-cutting tests was designed that would allow uncut coal to be left in the roof or floor while logging thickness predictions over these areas. These tests were more involved than the 2002 tests and were performed under the supervision of Monterey engineering staff.

Actual thickness of the roof and floor coal was measured visually (roof) or directly (floor) for comparison to predicted values. The object was to leave "in place" this uncut coal by cutting several steps into the face. The tests took place during the week of May 11 and again during the week of May 23. These tests were carried out in a section of the longwall panel that possessed only 5- to 6-foot coal thickness.

The floor data gathered were used to correlate predicted coal thickness versus actual thickness. The actual coal thickness, as well as Mine Height, is judged by averaging the section being measured. The exact position of a planar boundary in the seam is often difficult to delineate due to irregularities in the cut (scoured) surface.

The predicted and actual thickness values shown in this figure can be combined into a single "accuracy" plot that compares the values along a line of "perfect prediction." A perfect prediction has a ±0-inch error. This accuracy plot is shown in Figure 5.43. The floor data points are shown as blue dots. The green region running diagonally down the plot is the ±1-inch region where the HS-LW system exhibits the majority of its predictions.

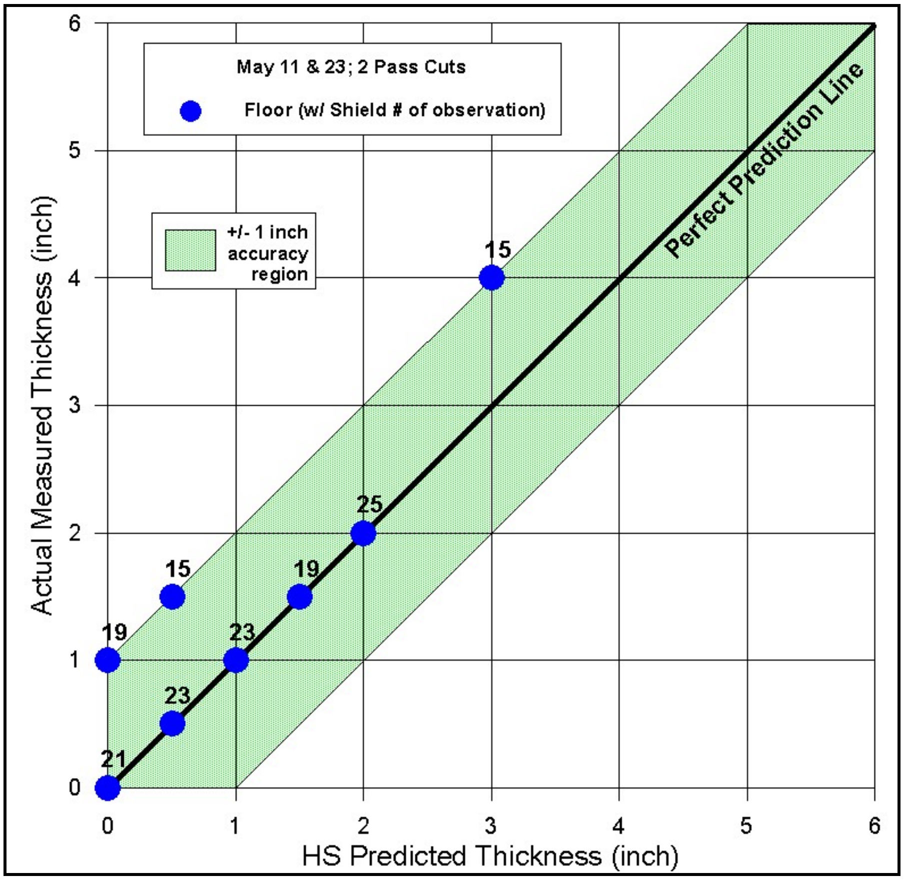


Figure 5.43. Accuracy plot for the floor predictions during the verification tests on panel 8E/1N

For the sake of discussion, prediction points of equal value are offset from one another on the plot. For instance, if two predictions of a 1-inch value are plotted, one would be graphed at 1 inch and the other at 1.2 inches. This allows the individual points to be seen and not obscured by one another. It is important to note that the HS graphics display only shows thickness to the nearest whole inch, and fractions or decimals of an inch are not shown. Even with the practical difficulty in physically measuring the actual coal thickness, the predicted values for the floor were within the ±1-inch range. This is better than the accuracy seen with the HS-CM system in the same mine.

Displaying the total mining height to the operator in real time has proven to be a critical tool for this particular mine due to a thinning coal seam and the need to maintain machine clearance. Setting the graphics unit to display mining height to the operator will save time, bit replacement, and rock reject numbers. The Total Mining Height indicator is accurately predicted on the HS to ±1 inch. In addition, the Current Mine Height indicator gives the position of the head above or below the desired cut so that the operator can monitor when too much material is being removed from the floor or roof.

Mining height predictions were not plotted since there was very little variation from the actual height (±1 inch over a 6.5-foot span). Both height indicators (Total Height and Current Height) perform with high precision and good stability.

As part of the verification process to demonstrate the benefit of the HS, Monterey management has shared the production data for April and May 2003—essentially a “before” versus “after” comparison. Table 5.6 shows the collection of production numbers compiled for the periods just prior to, and immediately following, the calibration of the HS-LW in May 2003.

Table 5.6. HS-LW Mining History at Monterey Mine for a month prior to HS usage and a month during HS usage

Production	4/1/03 to 4/30/03	5/1/03 to 5/31/03	YTD
Clean tons	246280	337685	1458907
Raw tons	407324	523737	2357195
% Reject	39.54	35.52	38.11
Feet of advance	1084	1451	6337
Avg. Mining ht. (ft)	7.00	7.00	6.6
Clean tons per foot	227.02	232.59	230.21
Raw tons per foot	375.47	360.75	371.96
Operating Hours	382.22	475.19	2214.69
Scheduled Days	30	31	151
Feet per scheduled Day	36.16	46.83	41.97
Feet per Day –Goal	50	50	50

DATE	STATUS
8/20/2002	HS installed on Shearer
10/25/2002	Start of new longwall panel
5/11/2003	HS calibrated for floor 0"-4"

The data show an improvement in production efficiency and percent reject yielding a cleaner ROM coal product, as well as a noticeable and measurable improvement in productivity. Several benefits are evident.

First, during May there was a 37.1% improvement in clean tonnage production, and a 28.6% improvement in ROM tonnage. While May had only one additional scheduled day of operation (shearers are planned to run 24/7 if possible), there was an additional 92.97 hours of operation, which obviously accounts for much of the production tonnage improvement of May versus April. However, increase in operating time is a 24.3% additional cutting time, yet the improvement of ROM and clean-coal tonnage is higher.

A second and key driver of production improvement is the reduction of "reject" or waste material, which the HS is designed to achieve. May production show barely a 4-point reduction in waste, which helps explain the additional clean coal yield above and beyond the impact of more operational hours.

Another noticeable and measurable benefit was the advancement of the shearer as measured in feet of advance. The advance in May was 33.9% greater, most of which was driven by the additional cutting hours, but the incremental improvement beyond the impact in time was achieved with cutting less rock as evidenced by the improved or lessened reject. Cutting less roof and floor rock enables greater cutting time for coal. The improvement of feet mined per day of 46.83 for May versus 36.16 for April was a significant 29.5% increase. During May when the HS-LW was utilized, the production crews came closer to their goal of 50 feet of advance per day.

Finally, while the cost data are confidential to Monterey, it is easy to estimate the cost improvement of using the HS-LW. This economic benefit is driven in part by the reduction in reject. The 4% improvement in yield coupled with the improvement in ROM tonnage productivity, Stolar estimates the improvement in operating cost is up to $1 per ton at the mine. This is based on an assumption of full cost of a representative shearer operation in the Illinois Basin.

The diagram in Figure 5.44 shows the longwall face cross-section for the 8E/1N panel through which the HS-LW-equipped shearer mined during 2003. This profile enables mining engineers to design a selective mining strategy.

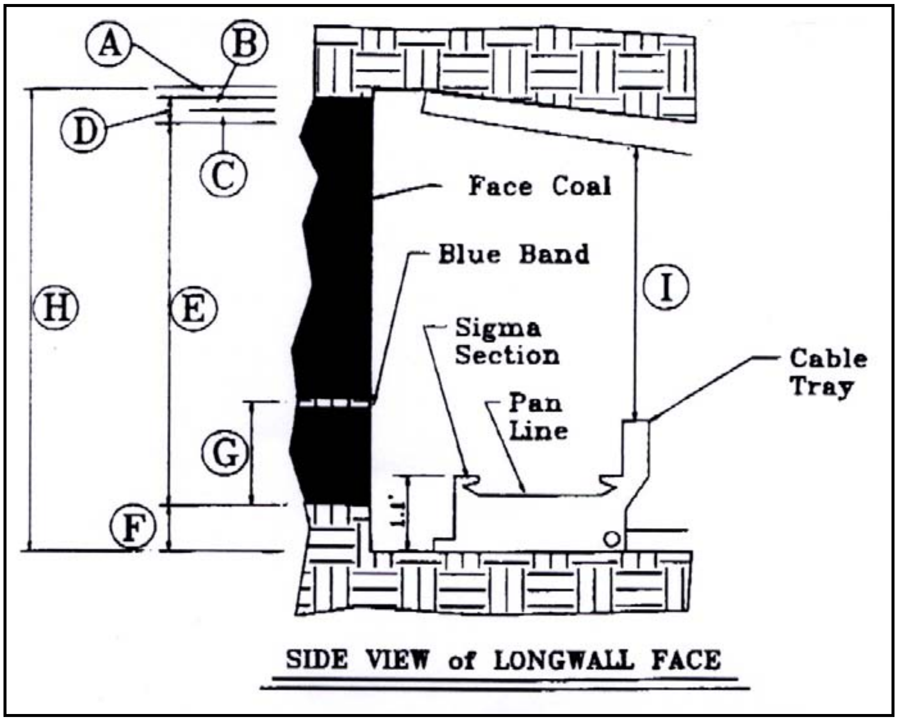


Figure 5.44. Cross-sectional diagram of the 8E/1N longwall panel face

Geologic analysis shows that in the layers from A to D, the content of sulfur, ash, and trace metals can be higher. Thus, detecting the boundary layer and mining a few inches below the roof or above the floor will effectively improve coal quality, as the May data above suggest.

Improving the quality and cost of coal production in Illinois are important goals for maintaining or increasing output in the state. As indicated above, there are several important benefits demonstrated in this CCT project. The team demonstrated that the HS-LW can detect the coal seam horizon, having done so on two Joy 4LS shearers. Detection of the coal horizon enables mining engineers to plan selective mining to reduce waste including sulfur, ash, and possibly trace metals. The production data of April versus May of 2003 show that indeed reject or dilution can be reduced, and in this sample, an almost 14% improvement was achieved, or a 4-point reduction of waste. Selective mining also improved or increased the volume of ROM and clean coal; mining advancement per day greatly improved, as one would expect, as more time is focused on cutting coal and not rock. These improvements translate into an economic benefit, estimated by Stolar at $1 per ton.

5.3.2 Ohio Valley Coal Company (TOVCC): One Joy 7LS Longwall Shearer

The Ohio Valley Coal Company (TOVCC), West Virginia University (WVU), and Stolar Horizon, Inc. (Stolar) conducted a demonstration of the HS-LW at TOVCC's Mine No. 6 in Alledonia, Ohio. The program was directed in accordance with the Ohio Coal Development Office (OCDO), which co-funded the program. The objective of the project was to demonstrate how the HS-LW could enable coal operators to employ a selective mining strategy to improve the quality of ROM coal by reducing ash, waste, sulfur, and possibly mercury. With a reduction of waste and pollutants, the ROM coal will be "cleaner" and more environmentally acceptable.

Such an improvement will enable Ohio coal producers to market their coals to a broader customer base. Additionally, the HS provides an added benefit of improving productivity and thus lowers mining cost. Reducing waste improves yield and lowers the ROM cost of coal. Cleaner ROM coal also improves preparation plant efficiencies and capacity.

Given the potential to produce a cleaner ROM coal, the HS-LW is essentially a CCT, which is a term traditionally applied to downstream or post-mining processing such as coal preparation and conversion, which is the generation of electricity at a power plant. The HS-LW is the first mining CCT, and its application in mining and support from the OCDO is consistent with the OCDO's objectives to promote coal-based R&D for technologies that will benefit the Ohio coal industry.

One HS-LW system was installed and used from May through September 2003 (one longwall panel). Installation of the HS-LW system on a Joy 7LS for TOVCC was partially completed early in April 2003. This installation, which took place at Joy Manufacturing's Homer City plant in Pennsylvania, included the display, inclinometer, and power-regulation components of the HS-LW system and did not include the drum-mounted sensor components. Stolar modified the shearer ranging arms by welding a removable shroud to the arms. This shroud provides a mounting location and protection for the MSHA-approved HGU and CBI enclosure onto the shield-side of each shearing drum. Electrical power required for the HGU electronics is provided using a GPIB mounted within the shearer's controller and connected to the machine's AC power supply. Installation time was approximately 12 hours. Figures 5.45 to 5.48 document the installation process of the HS-LW system onto the Joy 7LS shearer to be used at the TOVCC mine.

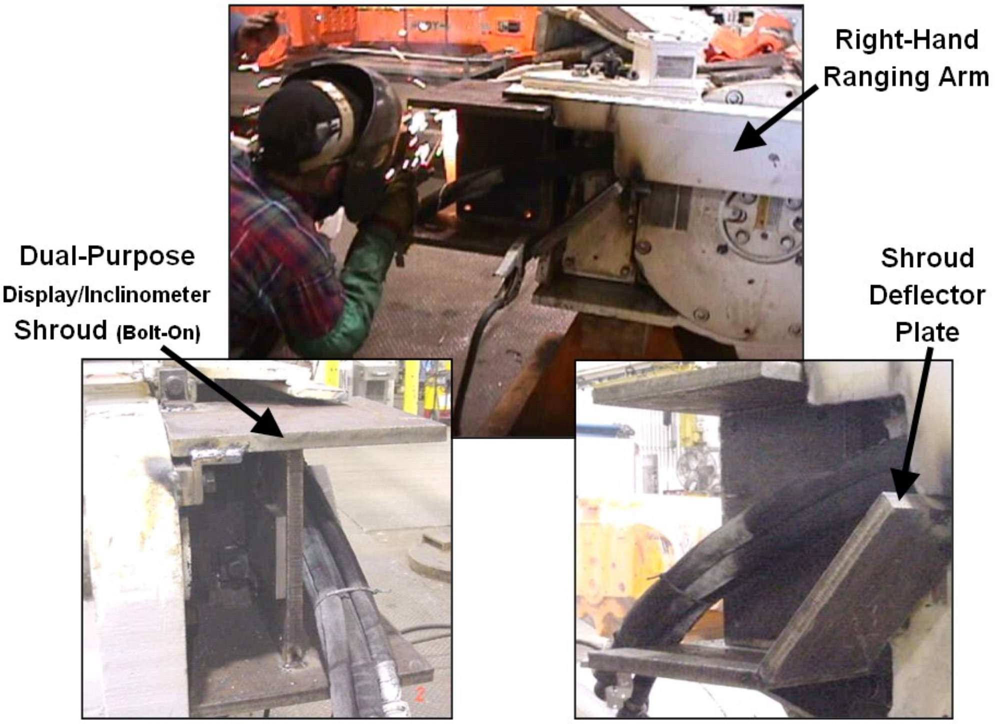


Figure 5.45. Installation of the HGU/CBI shroud on the right ranging arm. The shroud allows the components to be easily bolted-on or removed. The shroud itself also bolts onto the arm.

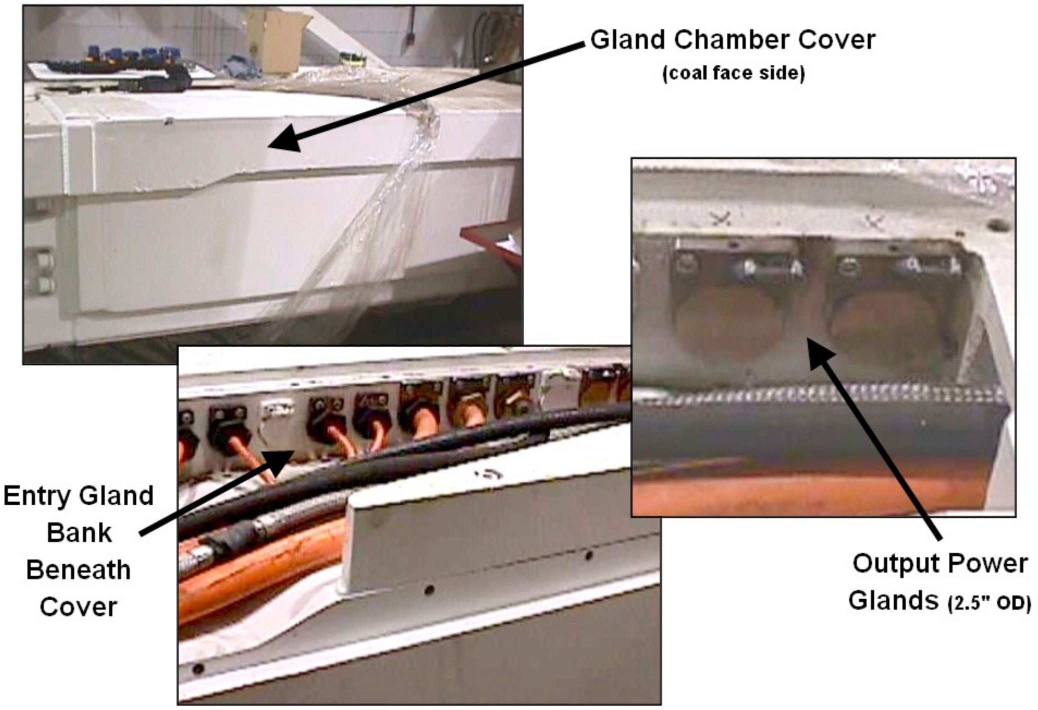


Figure 5.46. Entry-gland access panel on new shearer body (face-side). The glands will be used for the power cables that feed each of the two HGU displays. While the entry glands are 2.5" in diameter, the cables used are 0.5" in diameter (MSHA approved 18/5 SO Cable).

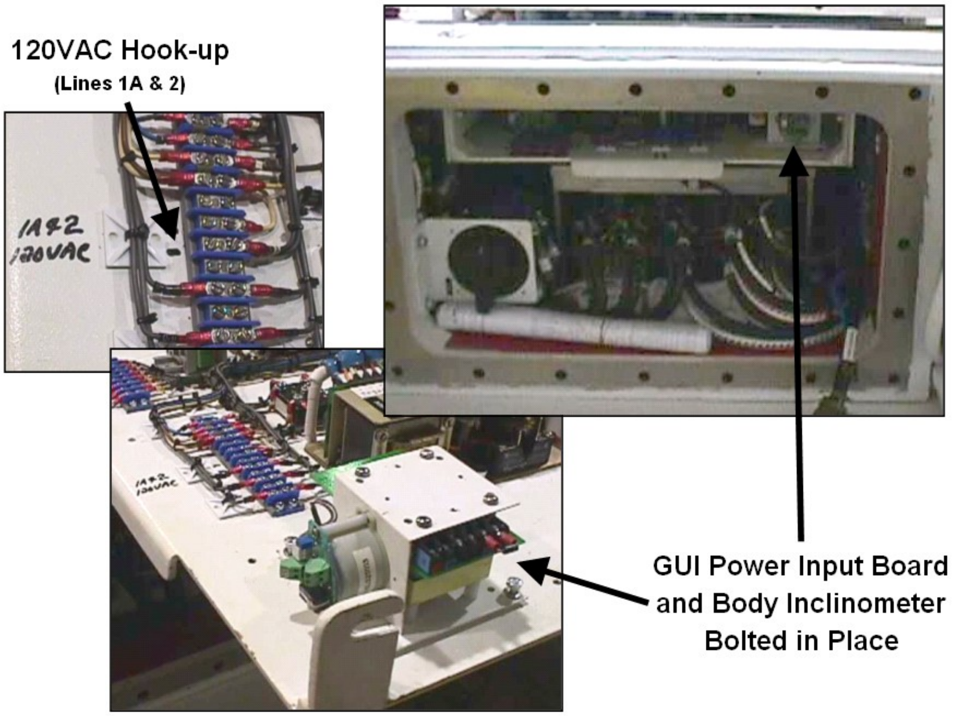


Figure 5.47. Installation of the GUI Power Input Board. The board receives 120VAC input power from the machine's #2 Terminal Block (lines #1a and 2). The output of the board is 20VDC, which exits the controller on 18/5 cables.

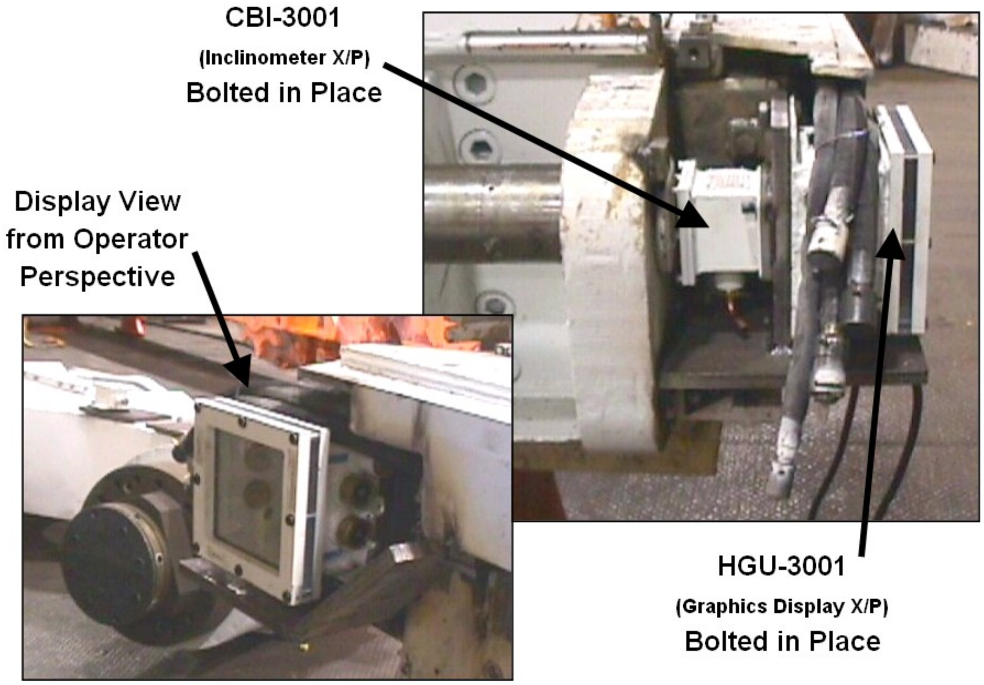


Figure 5.48 Installation of graphics display and boom inclinometer (HGU/CBI) and mounting/protection shroud on ranging arm

Stolar supervised the installation of the dual-display head-positioning system while the MSHA approval acquisition of a complete system was still in progress. During the week of May , Stolar went underground to finish the installation process at the longwall face. The Joy 7LS was on the face and the mine crews were setting up the longwall shields. Production was scheduled to commence on May 5. The final HS-LW head-positioning installation tasks included: attaching the HGU shrouds to both ranging arms; mounting the HGU and CBI enclosures to the shrouds; terminating the power cables, inclinometer cables, and GUI interconnect cable to the enclosures through the packing glands; and installing the HGU and CBI electronics into their respective housings.

The final step of energizing the unit at the face was postponed pending completion of the MSHA RAMP approval. Commissioning tests to verify system performance and accuracy would be completed once the unit was energized at the face.

The HS-LW drum-mounted sensor components were scheduled to be shipped for installation on the cutter drums. The type and source of the drums TOVCC needed was undecided in May. The mine anticipated a drum change on the machine late in July and would therefore order a set to be rebuilt in early June. They were using 32-inch depth (web cut), but wanted to go to 34 inches. At that point they scheduled Stolar to do its sensor installation at the rebuild shop after lacing and balancing of the drums was finished.

In June the MSHA RAMP was received so the unit could be energized. A longwall power-move took place on June 7 and the following tasks were completed: entered the two power cables through controller packing glands, installed GUI Power Input Board, initialized system power and setup parameters, and verified height accuracy during mining activity. The Stolar team also set up a training simulator that was used to train shearer operators on the functions of the HS-LW, as well as maintenance and permissibility issues. Prior to energizing the unit, Stolar provided training sessions above ground and at the face.

Final installation was rescheduled for mid-July, and commissioning tests to verify system performance and accuracy would be completed once the unit had sensors mounted and could be energized at the face. This could only occur once the drums were mounted. TOVCC had to accelerate the switch to a new set of drums. This rescheduling shifted installation of the HSU sensors from the Joy shop to the Mine 6 supply yard during the week of July 21. At this point Stolar examined the issue of fitting the housings on the drums. It was clear that the battery unit would be the only viable source of power because the HPU generator would not fit in the drum. Clearance for the housings appeared to be a concern, but the team was hopeful that there would be sufficient room for coal flow.

In August the Stolar team completed installation of the HS housings and, prior to installing the electronics, allowed for at least a week of mining to ensure the integrity of the housings. As previously reported, the MSHA RAMP was received on May 23, 2003. Since the HS has X/P approval, we needed to make sure the housings would not be damaged to put the effectiveness of the X/P safety feature at risk.

However, prior to electronic installation, the production crews reported maintenance and loading issues associated with the HS housing on the tailgate drum. This unexpected issue seemed to be a result of the hard cutting conditions at Mine 6, along with clearance issues. The coal flow appeared impaired, and concern was raised about potential damage to the drum bearings given a reported “bumping action.” Thus, maintenance management decided to remove the housings, which interrupted production for about 5 to 6 hours. A Stolar team visited the mine that day to investigate the situation. We note that longwall mining is a highly productive, but expensive process given the high investment and fixed costs. In the industry, management commonly uses a “rule of thumb” cost approach that each minute of lost production costs the mine several hundred dollars. In this situation, the removal of the housing was quite costly.

Given this unexpected development, Stolar decided to delay the sensing phase because the interruption to production was too costly. TOVCC management offered to immediately try to reinstall the housings, but Stolar decided it needed to better understand the cause of the problem prior to any new effort to install the unit. Stolar did not want a repeat of the problem.

Stolar contacted Joy to reconfirm that the bearings on the shearer drum are sized to adequately support the HS unit. Stolar also engaged Joy on the issue of sensor installation on shearer drums. As mentioned above, Joy was not an official party to this R&D effort and the team greatly appreciates Joy’s contributions to the program. The cost of Joy’s effort was not captured in the accounting of the program, but we note that there was cost showing that OCDO’s dollars were leveraged beyond the cost share agreed to.

Stolar then began to investigate the design of a “lower profile” housing to address the coal flow issue. Stolar repositioned the packing glands on the enclosures to allow installation at a level 3 inches closer to the drum shell. This design has the potential to improve coal flow through the veins and was submitted to MSHA for RAMP enclosure approval, which was secured in a few weeks. However, while the sensor housing might be size-reduced, there was another issue with power supply. The housing for the batteries could not be size-reduced, and, given the 24/7 nature of coal production on a shearer, it is not practical to power the sensor with batteries. The estimate of battery life would require daily change-out, which is estimated to take about 1 hour. This lost hour would cost about $25,000 per change-out, and thus the need for the Stolar HPU generator. In discussions with Joy it was revealed that indeed the HPU can be used, but the width of the drum needs to be at least 41 inches. This is not the case for the TOVCC drums, so a decision was made that the sensor option is not practical for this program. Joy also offered other design options on how to secure internal power generation. However, these solutions will take months of design and approval and are not practical for this program. Stolar will continue to work on this issue beyond this program. Joy has been helpful and will continue to work with Stolar.

In the meantime, mine management reported an encouraging benefit that the crews were beginning to utilize the head-positioning function, which was also a valuable technology for selective mining. A cutting procedure was devised that, when followed, would yield improvements in the waste rock mined during production. This cutting procedure involved the operator cutting the roof to keep his cutter head right at the level of the rock-coal interface, as visually determined. Then the operator cutting the floor could use the Total Mine Height estimate from the head-positioning functions to cut the minimum mine height required (usually 68 inches) for the shields to advance. In this process the floor rock was cut in lieu of the roof rock since it was a softer material. The low-seam conditions dictated that rock must be cut for the longwall to advance. The HS head-positioning functions allowed the floor rock to be mined in minimum amounts, improving yield and discarded waste rock. This cutting process had the additional benefit of aiding the operator navigating the cutter head through the seam in conditions of poor visibility.

A Stolar team visited the mine during the week of August 11 to ensure proper functioning of the system. The WVU team also visited the mine over the weekend to coordinate its effort. While the decision not to use the sensor was a disappointing development common to R&D efforts, the expanded use of the HP function to support selective mining was a positive development.

The Stolar team supported the effort to demonstrate the HP function. The team also modified the HS housing due to the previously identified profile problem, which occurred July 31. The team decided to ensure proper demonstration of HP, and hold the second HS housing installation as a next step. As indicated above, this was decided to minimize TOVCC production delays. The team wanted to make sure the next effort was an efficient one.

Mine management continued to report that the crews were using the HP function. One GUI display was reported down and Stolar dispatched an engineer to repair the screen. On September 16 maintenance and further training were performed. Stolar continued to coordinate the visits of WVU mining engineers to enable verification of the seam profile and HS-HP benefits. Their findings are documented in the appendices.

Head-positioning benefit studies continued into October as the team monitored the mining crew's effort to use the HP function. WVU's team went underground October 22 and 29 to observe operations. The WVU field reports are attached as appendices. The critical information is confirmation that the HP function enabled the crews to establish a fixed mining height that produced favorable results. As indicated in both reports, the HP function accurately measured mining height, and the HP function enabled the operator to cut the main bench and less roof and/or floor material (shale and rock). As also indicated in the reports, eliminating waste material reduces the waste in the ROM coal. In addition, the reports showed that concentrations of sulfur and mercury are avoided, and, given the minimal heat value of the shale and rock, there is a leveraging effect in quality.

In addition to reporting on the underground monitoring of the use of the product, the WVU report displayed important quality and geological information. The quality data depicts a profile of the bands of coal and rock. These depictions show how the ROM quality will improve with selective mining of the main bench. Also, WVU provided a profile of the longwall face showing the main geological bands of coal, shale, and rock, as well as the elevation. Note that the face is not level and has some undulations; thus, HP aids the operator as the shearer works across the face.

In our discussions with mine management, they reported that the crews were using (or had used) the HP function over a several month period. The HP function provided real-time readouts of the mining height and drum position, which were intended to support the positioning of the sensor, but now proved to be very useful to the operator. While the thickness detection would be the best option, the HP function proved effective and demonstrated potential use for all shearers and CMs. The WVU field reports and management's observations are consistent.

During this program the team spent time training operators. Stolar provided a special training model that was left at the mine office. Stolar's representative held training sessions at the start of the project, but also a retraining effort once the HP system was fully functioning. TOVCC management indicated that the training efforts were effective. The Stolar team also set up a training simulator that was used to train shearer operators on the functions of the HS-LW as well as maintenance and permissibility issues. Prior to energizing the unit, Stolar also provided training sessions above ground and at the face. This simulator was delivered to the mine on May 4 and was kept in their training room during the duration of the program.

During the program, the team management determined that additional training was needed once the HP function was fully employed. Stolar dispatched a technician to the Mine No. 6 office to conduct a special training session. The training simulator is shown in Figure 5.49.

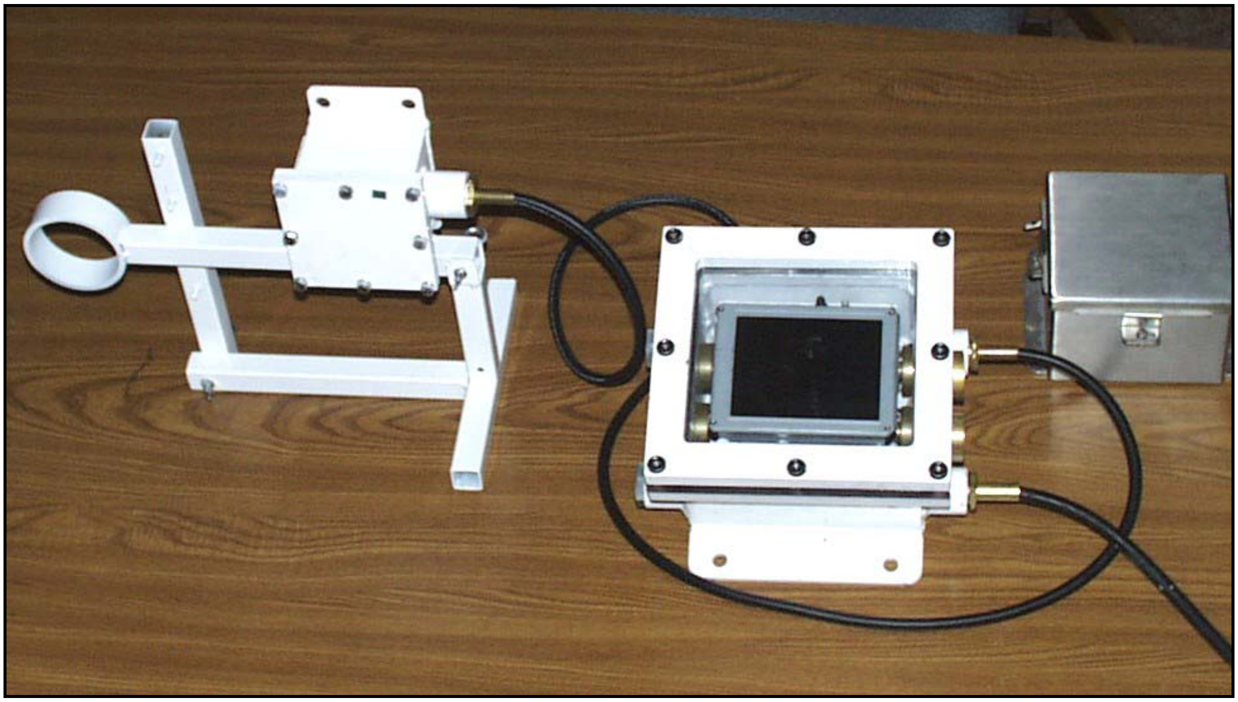


Figure 5.49. HS-LW Training Simulator including the Power Supply, Display, and Inclinometer

The team worked early in the program to develop a selective mining strategy since it was confirmed that the initial mining phase of the panel would take place in a thinner section, resulting in possible out-of-seam mining given the drum diameters. Thus, during the early phase of the project, the team expected to focus on HP and a minimum mining height strategy to reduce waste and improve yield.

As the mining approached the middle of the panel, where the coal thickness was estimated to increase to 63 inches, the horizon-sensing function of the HS-LW product would be installed. During this section of mining, the team would focus on horizon detection to leave behind boundary coal layers that have higher sulfur and ash concentrations. This would also be an opportunity for the HS-LW to detect the bottom horizon of the 10- to 12-inch draw rock. Elimination of mining the draw rock would greatly improve ROM coal quality.

WVU was assigned to monitor the mining activity and document the quality of ROM coal from Panel 23 West to determine that indeed an improvement of quality was being achieved. Additionally, WVU would examine geology to identify the sections of the seam that had higher concentrations of sulfur and ash. WVU would also attempt to determine if concentrations of mercury could be identified near the roof and/or bottom. If such were the case, the team would attempt to demonstrate a reduction of mercury in the ROM coal. A plan was developed by Stolar and WVU to sample and monitor coal quality during this program.

A key task of this project continued to be the quality-monitoring tasks during August. During the final 2 weeks of mining in August, WVU completed two face profile studies on the longwall. These studies showed important conclusions about the "in-place" coal quality. Assessing quality of the seam in increments of 6-inch sections was a valuable exercise. As suspected, the concentration of sulfur and ash is higher in the top or rider seam. The shale band, as one would expect, is essentially all waste material. Selective mining to cut underneath the shale will obviously improve ROM quality. An important aspect of the quality analysis is the concentration of mercury. While mercury is present throughout the channel samples, there is a slight concentration in the top 6 inches of the main bench. This is seen especially when one adjusts for the heat content of the coal. With such an adjustment, the mercury per trillion Btu is measurably higher.

The work performed by WVU on coal quality sampling and analysis confirmed that known pollutants, such as sulfur and mercury, are found in greater concentrations at the boundary of the coal seam. The work from WVU provides a thorough analysis of the seam and surrounding boundary rock and confirms there is a higher concentration of sulfur and mercury in the top 6 inches. Figure 5.50 shows the channel sample and the points at which WVU engineers segmented the sample to achieve quality by "bands" along the vertical of the sample.

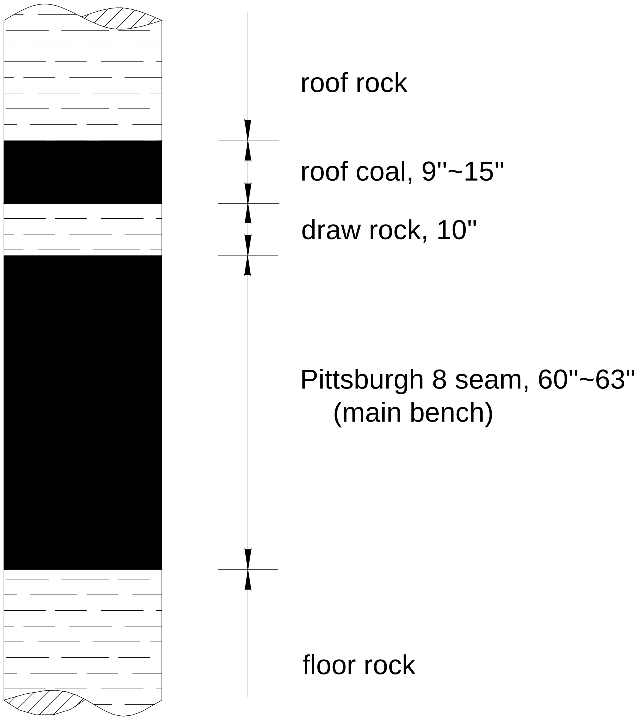


Figure 5.50. Seam thickness profile 23 West Panel

The study showed that the concentration of sulfur is highest near the roof (the top 6 inches of the main bench of the Pittsburgh 8 seam), as well as the draw slate and rider coal seam. WVU engineers point out that most of the sulfur is organic so there is little opportunity to remove sulfur through washing. Reduction of sulfur can be achieved by leaving behind the draw slate, rider seam. and several inches of the top section of the main bench. Sulfur reduction in ROM coal can range from 5% to 10% on a weight basis.

Also, as WVU shows, mercury (Hg) is found in the draw slate and the floor boundary rock as measured in parts per million (PPM)—0.21 PPM in the slate, but also at a higher concentration in the top 6 inches of the main bench. Analysis of the data confirms that selective mining will enable improved ROM quality coal (less ash, sulfur, and mercury), which is of benefit to the industry.

Less ash is of benefit for several reasons. First, the cutting of ash and rock in the roof and floor is a waste of time and mining resources. Focusing just on the draw slate, the WVU analysis shows this waste material to be about 10 inches "thick." Given the width and length of Panel 23W (950 feet by 13,000 feet), eliminating the 10 inches of draw rock/slate will improve yield about 14% (10 inches divided by 70 inches, which is the total mining height to the top of the slate). Also, over the full length of the panel, the draw rock represents over 450,000 tons of waste material that can be left behind in the mine. Second, there is a direct cost benefit of cutting less rock because more time can be consumed on cutting the primary product, which is coal. If the 7LS and transport system does not have to cut and transport 450,000 tons of waste, it can cut and transport about the same amount of coal. Thus, there is a direct cost benefit to increasing yield.

In this program the economics of TOVCC's production is proprietary information. However, with each percentage of yield improvement, there is a direct and corresponding improvement in lower production cost for ROM coal. With a 14% yield improvement there is the potential for a 14% cost improvement (again for ROM coal), making the production more competitive in the market.

However, from a CCT perspective, reduction of rock and ash has several environmental benefits. Aboveground ash disposal in either gob piles or settling ponds is expensive and, over time, considerable land area becomes waste area. Estimates vary but disposal costs can be from \$2 to \$3 per ton to, in some cases, over \$10 per ton. The elimination of draw slate in a panel can significantly reduce costs.

Additionally, reducing the ash in ROM coal provides for more efficient preparation plant operations. There are capacity improvements and lower processing costs. These enable lower ash content in the finished product, which is an added benefit for power plant customers. Less ash can improve thermal performance of coal at the plant, improving heat rates.

When WVU witnessed TOVCC production cycle with HP being used for selective mining, staying below the slate band eliminated 8 to 12% rock waste from the seam Along a similar track, selective mining below the slate can reduce sulfur in ROM coal by up to 10%, and mercury as much as 25%. Mercury will be reduced by leaving behind the slate and rider coal and a portion of the top 6 inches of the main bench. WVU engineers also note an important fact that mercury can be removed in part through the washing process (33%), thus a "cleaner" ROM coal will aid in the reduction of mercury. This 33% reduction is consistent with information available from other coal companies. These are important impacts given the requirements under current regulations to restrict sulfur or SO2 emissions, and pending reductions of mercury emissions. This is a process that could assist companies marketing Eastern coals, which have higher concentrations of mercury.

With mercury, the findings are important given proposed regulations to reduce mercury. There are other downstream solutions for removing and/or reducing mercury, but given the fact the HP function can enable selective mining for several benefits, the reduction in mercury can be viewed as an added benefit, which will be of value to the industry.

As a result of this demonstration, Stolar has received new inquiries for application of HP and HS in mining. This is an encouraging outcome showing the need for a technology that can enable selective mining.

The benefits of selective mining to improve ROM coal quality are important to the industry. Selective mining strategy was a topic of discussion at the 2004 SME Annual Meeting held in Denver the week of February 23, at which Stolar discussed the outcome of this project. The critical finding of this project is that selective mining can be achieved with the HP function whereby the operator of a mining machine can fix the mining height. The use of HP on the Joy 7LS confirmed that the operator would sufficiently control the cutting drum position to leave behind roof rock and harmful elements, such as sulfur and mercury.

As depicted in Figure 5.51, the shearer drums are set to cut coal from the face at a "selected" cutting height. The drums are positioned and can be moved. It was the intent of this project that the HS would be used to automatically direct the cutting height—for example, setting the HS to leave behind 3 inches of "top" coal on the main bench along with the slate band and rider coal above the slate. However, the Pittsburgh 8 seam in this region is fairly consistent, enabling the operators to use HP to set cutting height. As reported by WVU engineers, the operators indeed used HP to selectively mine the face.

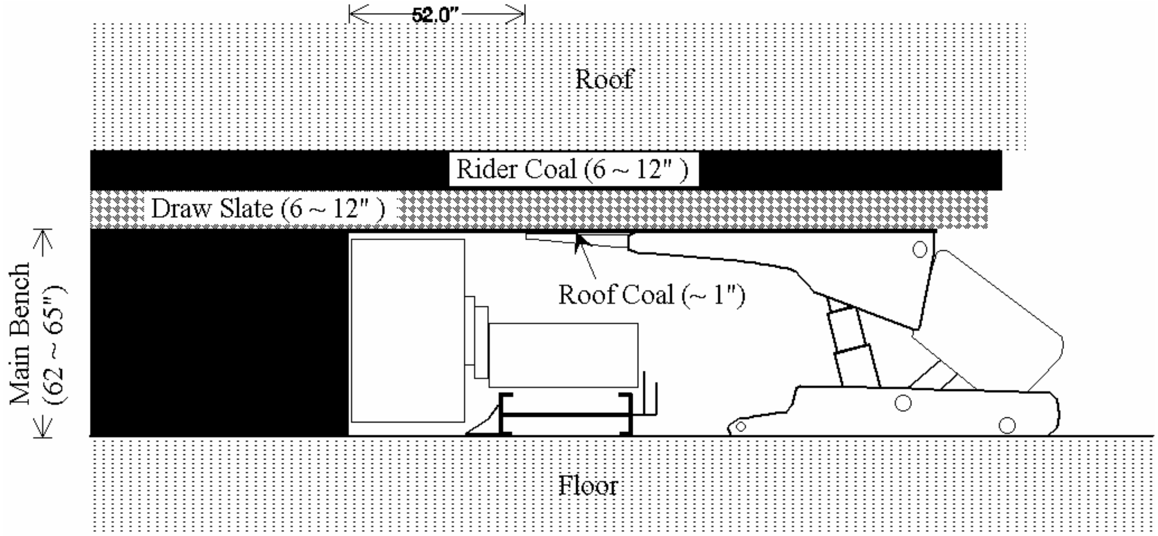


Figure 5.51. Current longwall mining practice in TOVCC

The data presented by WVU show that these elements are in higher concentrations around the top boundary of the seam. Leaving them behind will materially improve ROM coal quality. At a time when greater attention is being drawn to providing cleaner coal, including reduction of ash, sulfur, and mercury, this project has provided valuable data for the industry.

This program met its objectives to demonstrate that the HS-LW technology has positive impacts on coal quality. However, there is one exception concerning the use of the sensor, as will be explained below. One complete HS-LW system was mounted on the TOVCC Joy 7LS shearer. The HS-LW includes an HP system, which is an important feature or component of the Stolar technology. The plan was to use the complete HS-LW system to employ a selective mining strategy. The HP function was demonstrated and used by the shearer operators to employ a selective mining strategy that reduced mine waste and ash, sulfur, and possibly mercury. As shown by the WVU coal quality analysis and field reports, the use of the HP system is an effective CCT. We estimate that sulfur and mercury can be reduced up to 10% and 25% in ROM coal, respectively.

The key to quality improvement rests in the fact that the WVU coal quality analysis shows that there is a higher concentration of pollutants at the boundary of the coal seams. During the coal depositional process that occurred millions of years ago, geologists would agree that these elements would concentrate especially at the top of the seam. The WVU analysis confirmed this phenomenon, which is the basis for considering a selective mining strategy. The program moved on to the demonstration of the equipment. WVU's observations confirm that the strategy is viable.

Thus, key findings that support the Program Objective are: 1) the WVU analysis confirms that selective mining has the potential to, and can improve, ROM coal quality given the concentration of pollutants in bands of ash, sulfur, and mercury; 2) the Stolar HP function on the HS-LW can be used as a stand-alone "tool" to prosecute selective mining for positive results; and 3) the sensor unit's battery pack precludes installation on small drums, and requires self generation and not batteries. Stolar and Joy are already cooperating on resolving this issue, which is a long-term positive outcome of the program.

6. HS Program Conclusions

Over the course of this 3-year program, the experiences of installing and operating 14 independent Horizon Sensor (HS) systems have provided innumerable engineering and implementation lessons. Each installation presented its own challenges and much was learned and optimized. Experience showed that installations of HS can be done on existing mining machines underground, as well as in rebuild shops. Installation did not compromise the machine's mechanical or operational capabilities and the HS output was kept independent of operator control and used strictly as a visual aid.

In the final two years of development the HS design was robust and HS system maintenance was low due to vibration dampening and system construction. HS part replacement is done fairly rapidly due to a small modular design, and availability of the equipment was found to be normally above 95%.

The Horizon Sensor detection and positioning capabilities are listed below:

- HS can measure and predict uncut coal thicknesses of 0 to 10 inches with ±1-inch accuracy.
- HS can measure and predict uncut coal thicknesses of 11 to 20 inches with ±2-inch accuracy.
- Equipment can be configured to maintain a cutting zone when cutting is done outside the coal seam limits.
- HS can measure and display total distance traveled by the cutter head from roof to floor with 1-inch accuracy.
- HS can monitor real-time location of the cutter head within its travel path with 1-inch accuracy.
- HS can be used to detect sump depths between 10% and 90% drum diameter.

Using the case studies from 3 years of HS demonstration and documentation, an itemized list of the key benefits can be concluded. These benefits include capabilities and conditions for the operator, improving the mining environment and production capabilities, and improving the end product.

Improving the capabilities and conditions for miner operators:

- Provide ability to accurately direct the cutter head, providing a greater degree of control.
- Operator training aid for sump cycle accuracy and consistency.

- Display aids the operator during poor visual conditions caused by dust, water, poor lighting and obstruction of view.

- Keeping the cutter head out of bounding rock reduces the generation of silica dust.

- Moves operator further back from miner, reducing his exposure to airborne dust and noise.

Improving the mining environment and production capabilities:

- Maintain consistent, or minimum, entry heights for machine clearance.

- Efficiently track the undulation and trend of coal seam strike and dip.

- Maintain consistent uncut coal horizons to avoid high sulfur and ash coal near bounding rock.

- Improves roof control by leaving known uncut roof coal.

- Consistent floor coal prevents machine breakthrough.

- Minimizes out-of-seam dilution by selectively cutting coal, reducing rejected material during processing.

- Less waste to remove will increase plant capacity and allow the plant to operate more efficiently.

- Increase cutter bit life by keeping the cutter head out of denser material.

- Increase cutter and haulage motor wear by cutting and transporting less weight per cycle.

- Improve conditions in longwall gate entries (ventilation, travel ways).

- Enables automation of sump-cut cycle or shearer pass control.

- Forward-detection capabilities can prevent cutting into faults, dikes, or water-filled voids.

Improved end product:

- Cleaner run-of-mine (ROM) coal will create costs savings at the preparation plant.

- Improved coal quality increases coal value.

- Increases preparation plant yield and bypass.

- Cleaner coal improves power plant economics.

The Horizon Sensor is an innovative and breakthrough technology, mounted directly on the cutter drum of a coal mining machine, that provides valuable, real-time sensing of the coal seam horizon and the potential to reduce cost by $1 per ton. In the United States, coal companies produce over 1 billion tons per year, about half from underground mines at an average value of $20 per ton.

The benefits to HS customers have been evaluated during all 14 installation and usage programs in the course of this 3-year program. The benefits involve more accurate cutting of only coal in a given seam and thus reduced waste, fines, and improved production yield. Improving yield improves the economics of mining and improves the quality of the coal product. Improving coal quality creates meaningful benefits for end users, such as utilities that produce electricity from coal.

Because of improved coal quality, HS is considered a clean-coal technology (CCT), providing benefits to the environment. Additionally, HS is a critical “enabling” technology required for full automation and agile mining. Once a dependable user history is built around the HS system, equipment manufactures will begin to develop more direct interfaces between their mining machines and the HS system.

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