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CONVEYANCE MONITORING TO IMPROVE MINE HOISTING SAFETY

Michael J. Beus and Todd M. Ruff
Spokane Research Center, National Insitute for Occupational Safety and Health
E. 315 Montgomery
Spokane, Washington 99207 USA

William G. McCoy
McCoy Engineering
Spokane, Washington 99208 USA

Abstract. ***Technology to enhance safety during mine hoisting is being investigated by researchers at the Spokane Research Center National Institute for Occupational Safety and Health. The objective is to test sensor technology and engineering controls to prevent injuries and fatalities related to vertical movement of personnel and materials in mine shafts. Improved monitoring and inspection technology will provide operational data on the mine shaft conveyance to a hoist operator in real time and warn of potentially dangerous situations.***

Assessment of current technology determined what conditions and equipment should be monitored and the availability of appropriate sensors. A state-of-the-art hoisting facility was constructed, and new sensors and data acquisition interfaces were developed. A computer-based system controls the hoisting motor, material loading and dumping, and related hoisting functions. A new sensor was developed to determine conveyance loads and slack and tight rope conditions. Data on wire rope tension, conveyance posi-tion, and guide displacement are being acquired with a custom-designed data acquisition board. Data transmission up the shaft has been successful for a distance of 600 m (1800 ft) via 2.4-GHz, spread-spectrum modems when using a directional antenna. Data are received with a patch antenna and transmitted to the serial port on a personal computer and processed with a Visual C++ computer program.

1. INTRODUCTION

Researchers at the Spokane Research Center (SRC) of the National Institute for Occupational Safety and Health (NIOSH) have constructed a shaft and hoisting research facility and developed new sensor technology to improve the safety of mine hoisting operations. This paper describes the research facility, retrofitting of the hoist motor with state-of-the-art control components, and development of a sensor and data acquisition system to monitor mine hoist conveyances. The goal of the research is to improve monitoring, inspection, and control systems to increase awareness of the proper functioning of mine hoists and to develop means of warning of potentially dangerous situations.

A mine shaft is the lifeline to underground mines, and miners depend on safe, uninterrupted, and efficient operation. The shaft and hoisting system provide access to the network of openings used to recover the underground resource, provides vertical transport of miners and materials, and serves as an escapeway in case of emergency. Accidents involving hoisting can be catastrophic, such as at the Markham Colliery in Derbyshire, UK, in 1973, when the conveyance overwound and fell to the pit bottom, resulting in 17 deaths. According to Mine Safety and Health Administration (MSHA) data, many shaft-related accidents in the United States are associated with the hoisting and loading-unloading cycle. Hoist and elevator machinery must meet the requirements specified in the Code of Federal Regulations (CFR), Parts 57 and 75.

Earlier investigators have defined safety features and operating and maintenance standards for hoists and reported on monitoring and control systems and sensors for hoists and conveyances [1-5]. Based on these investigations, SRC researchers determined that there are several shortcomings in hoisting technology that require investigation. The project has thus evolved two research topics: (1) development of a state-of-the-art hoisting research facility to evaluate process control technology for mine hoists and (2) development of a conveyance-mounted sensor and

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data acquisition and transmission package to determine rope tension, conveyance weight and position, and guide displacement.

2. MINE HOIST RESEARCH FACILITY

Figure 1 shows the layout of the closed-loop mine shaft and hoisting test facility that has been constructed at SRC. Ore is initially loaded through a ground-level grizzly into a gated, below-ground discharge chute and loading cartridge, and then into the skip. The loading cartridge is equiped with balancing load cells to monitor the net weight of material in the cartridge prior to its discharge into the skip. Weight detected by these cells in relation to loading gate position controls skip loading functions. The skip hoists the ore to the top of the headframe, where it is dumped into a hopper. The ore is gravity-fed through a one-third-scale mockup of an ore pass chute and gate system. The material is then dumped into the below-ground hopper and loading pocket, completing the loop.

The hoist room components include a winding drum, gearbox, braking system, and a 37-kW (50-hp) dc motor to drive the hoist drum. A 6-to-1-gear reduction is achieved with a Rex planet gear speed reducer. An additional speed reduction of 2-to-1 is achieved through a chain drive sprocket on the drum. The hoist drum is 76 cm (30 in) in diameter and has a capacity of 152-m (500 ft) of 9.5-mm (3/8-in) diam wire rope. The skip conveyance is designed for 227- to 454-kg (500- to 1000-lb) net hoisting capability over 24 m (80 ft). The concrete lined "shaft" section is 5.5 m (18 ft) deep and the hoist tower-head-frame is 18.3 m (60 ft) high.

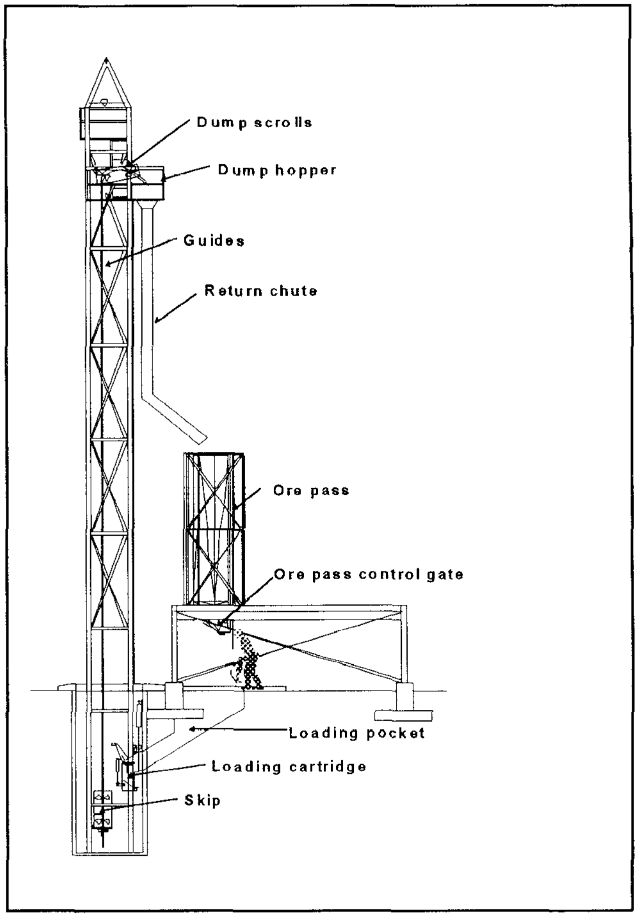

Figure 1.—Hoist tower and headframe

3. HOIST CONTROL

A state-of-the-art, computer-based system controls the hoist motor, ore chute gates, and related hoisting functions. Hoisting and loading operations can be controlled manually or the system can be allowed to cycle automatically through the loading, hoisting, and dumping process. Motor control is achieved with a Saftronics DCM-series motor controller. The control functions are performed by a 16-bit microprocessor. Control parameters are entered on a keypad and stored in electrically erasable, programmable, read-only memory (EEPROM). An RS485 serial interface is also available for inputting control parameters and monitoring outputs with a personal computer (PC). An automatic tuning procedure is run with no load during setup and provides feedback parameters for precise motor control.

Control functions include run, stop, motor direction, and motor speed. The run and stop controls are defined by adjustable velocity profiles. Two separate maximum motor speeds are used, depending on the skip's position in the shaft. The first velocity profile for a maximum motor shaft speed is 400 rpm, or a conveyance velocity of 0.5 m/s (1.4 ft/s). This speed is used while the skip is traveling between stations. As the skip approaches the loading or dumping station, a second maximum speed reference, or creep speed, is used. A maximum motor speed of 50 rpm is used in these areas to position the skip at the station. Two limit switches are mounted near the top of the shaft and two near the bottom. The limit switches are momentarily closed as the skip passes, which activates the appropriate motor speed (400 or 50 rpm) or stops the skip at the station.

An electric brake system manufactured by Warner Electric is installed on the motor shaft. While the regenerative capabilities of the dc motor are sufficient to stop a full skip, the brake system provides a positive and safer method of stopping. Brake control is achieved through a Warner Electric torque-adjustable brake controller. The brake provides maximum static torque at a input voltage of 90 V dc, which is provided by the controller. When the stop button is activated, the motor begins ramping down; however, the braking action is delayed for the duration of the ramp-down before the brake is set.

Motor speed feedback is achieved with a Rotopulser encoder and a Dynapar frequency-to-voltage converter. These units function as a tachometer at a greatly reduced cost when compared to purchasing a conventional tachometer generator. The encoder consists of induction proximity sensors that sense the teeth of a motor shaft-mounted gear. The resulting output signal is a square wave with variable frequency. This signal is converted to analog voltage by the frequency-to-voltage converter, which provides +10 to -10 V proportional to motor shaft speed and direction. This signal is then be used by the motor controller for speed feedback control.

A Windows-based human-machine interface (HMI) software and programmable controller technology are used for hoisting automation. This expands the amount of automatic control functions possible for the hoist. A General Electric Fanuc series 90-30 programmable logic controller (PLC) runs the logic for both manual and automatic operation. Wonderware's Intouch HMI software is used to provide the operator interface. This software runs under Windows 3.11 on an industrial 486 DX touch-screen PC. A control panel is currently set up to provide the operator interface for operating the hoist manually. The panel consists of speed-control potentiometers, hoist motor controls, valve controls for the loading gates, and a flat-panel, touch-screen PC to run the HMI software.

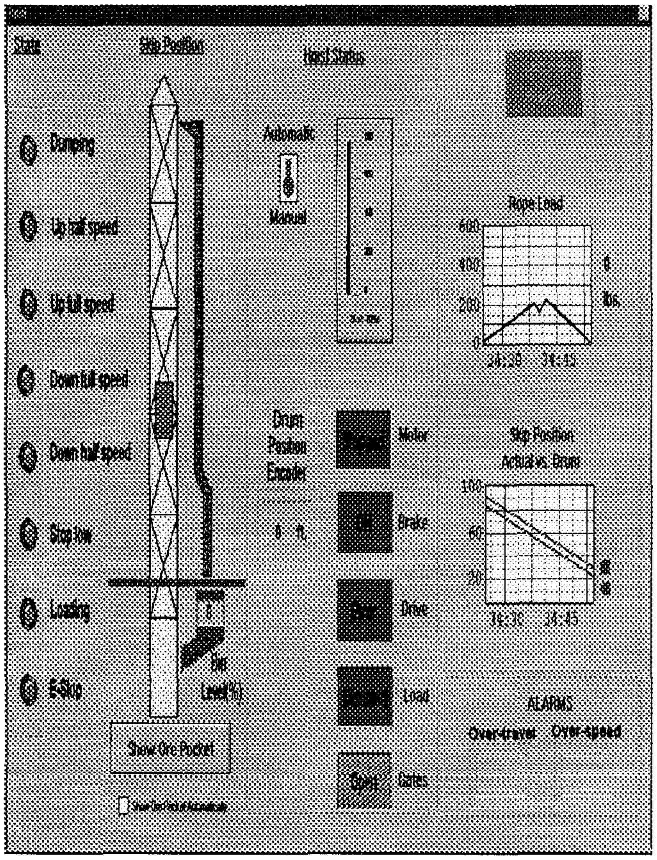

Figure 2.—Hoist graphics control screen

Figure 2 shows the main process control screen for the hoisting system. All sensor inputs and PLC outputs are monitored from this screen. Hoist operation can also be controlled from the screen; however, the hard-wired buttons on the control panel override any command given from the touch-screen. Real-time graphs are used to monitor and record values such as rope load and skip position, as shown in the lower right of the screen in figure 2. These graphs are easily set up and are especially useful for evaluating the most effective sensor types and configurations. For example, optical encoders are mounted on the hoisting drum and on the skip to determine the position of the skip in the shaft. These sensor values are recorded to aid in determining the effects of rope stretch and other errors that may occur in sensing the skip's posi-tion based on the Rotopulsar data. Detailed views of the hoisting and ore-loading process can also be accessed from the main control screen. For example, pressing "Show Ore Pocket" brings up the loading pocket screen. Operation of the loading chutes and gates, ore levels and loads in the bin, and conveyance net weight loads can all be viewed from this screen.

Automatic operation of the hoisting, dumping, and loading processes is controlled by a ladder-logic program in the PLC. In automatic mode, the status of the process can be viewed on the left side of the main control screen. Automatic operation allows the system to cycle through the loading, hoisting, and dumping processes without manual intervention.

A Simplex model Lilly control system was installed to study possible interactions and safety issues arising from retrofitting of Lilly control and hoisting systems with automated digital controls systems. Lilly controllers have been the standard mechanical control devices for mine hoist installations since the early 1900's and are still typical at mining operations. They operate as skip position indicators and stop the winding drums and apply brakes in the event of overspeed and overtravel. A centrifugal governor is driven in synchronization with the hoist drum to track the speed of the skip. A pair of cams moves in proportion to skip position and trips a limit switch to turn the motor off automatically and set the brake if an overtravel condition is reached.

4. CONVEYANCE MONITORING SYSTEM

Development of a shaft conveyance monitoring system has focused on determining conveyance position, velocity, acceleration, load, wire rope tension, and guide displacement. Previous work [6-7] described initial concept development and application of Visual Basic computer programs for data processing. The current work involves laboratory and field evaluations of sensors, data transmission schemes, and data processing using the Visual C++ programming language.

The system is designed to provide hoist operators and maintenance and inspection personnel with a real-time indication of the operational status of a mine shaft hoist conveyance. Status information provided by the monitoring system enhances the safety of mine personnel during normal conveyance operation and is useful as a means for acquiring shaft inspection and maintenance data. The concept for the conveyance-mounted system (figure 3) consists of sensors, sensor signal processing electronics, battery, power supply, and the transmitting end of a data link. The receiving end of the data link, located at the collar of the shaft, provides sensor data to the serial port of a desktop PC in the hoist control room. The same information is also transmitted to a laptop computer or terminal on the conveyance for inspection or maintenance purposes.

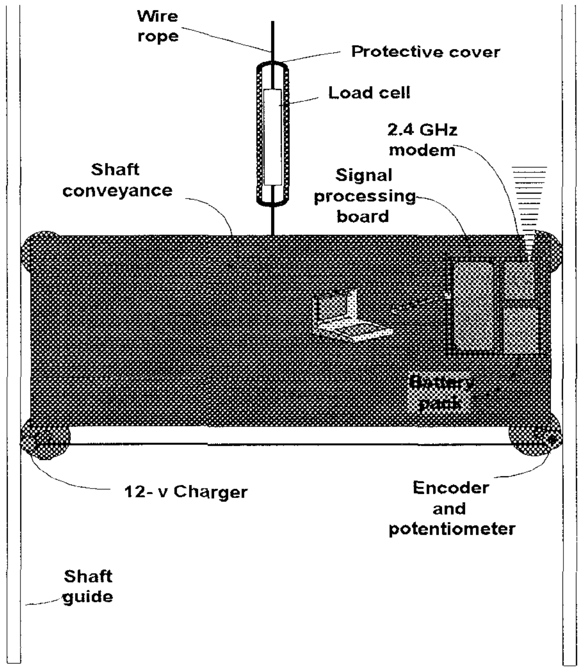

Figure 3.—Layout for signal processing board, battery pack, wireless data link, and sensors

A. Conveyance Sensors

The sensors mounted on or near the conveyance detect wire rope tension, slack and tight rope, conveyance load, hoist and elevator position, and hoistway guide rail misalignment. The most important parameters are conveyance load and wire rope tension. Movement caused by seismic events, such as rock bursts, or other obstructions in the shaft can cause conveyance shaft guides to become distorted. If the conveyance should become stuck in the hoistway, a condition of slack or tight rope will result, depending on whether the conveyance is descending or ascending. This can be merely a potentially hazardous incident, with only minor safety implications for personnel. However, if a hoist operator is not aware of the situation or does not immediately take corrective action, the rope can be damaged and may break, leading to a major catastrophe with significant loss of life such as occurred at the Markham Colliery.

Previous approaches to monitoring conveyance load have favored in-line load cells in the wire rope load path located at the conveyance termination, compressive load cells located at the sheave wheel pillow blocks at the headframe, or load cells or strain gages mounted on the structural support members of the conveyance itself, such as the crosshead. The major disadvantage of compressive load cells at the head sheave is that they sense the *total* downshaft load, including weight of the wire rope. Both the in-line load cells and the compressive load cells must be high capacity to accommodate the required safety factors of the wire rope and sheave wheels. This reduces load sensitivity so that small but significant changes in con-veyance load and wire rope tension cannot be deter-mined. The disadvantages to using in-line load cells are that they are part of the support structure of the convey-ance and might compromise the strength and safety of the wire rope conveyance system. Crosshead-mounted devices are subject to errors from extraneous loads and nonuniform distribution of conveyance weight.

A sensor developed at SRC overcomes these disadvantages. This device determines conveyance weight by measuring beam-bending strains resulting from the normal load component of tension on the hoist cable. As the wire rope undergoes loading and unloading cycles, normal force components produce bending strains at the midpoint of the cell body (figure 4). The bending strains are measured with a full bridge circuit, and a millivolt signal is obtained corresponding to a calibrated tensile force. The device is attached to the wire rope so it is completely isolat-ed from the wire rope load path, and therefore there is no effect on the wire rope safety factor. The attachment principle ensures that only bending strains are produced at the midpoint of the cell body, which results in excellent sensitivity and load resolution for all sizes of wire rope. Linearity and hysteresis are controlled through the use of Belleville disc springs configured so that they produce a regressive deflection curve. Crosby clips ensure that standard wire rope termination hardware can be used and that wire rope entry and exit points are properly realigned to eliminate abnormal flexural strain in the rope.

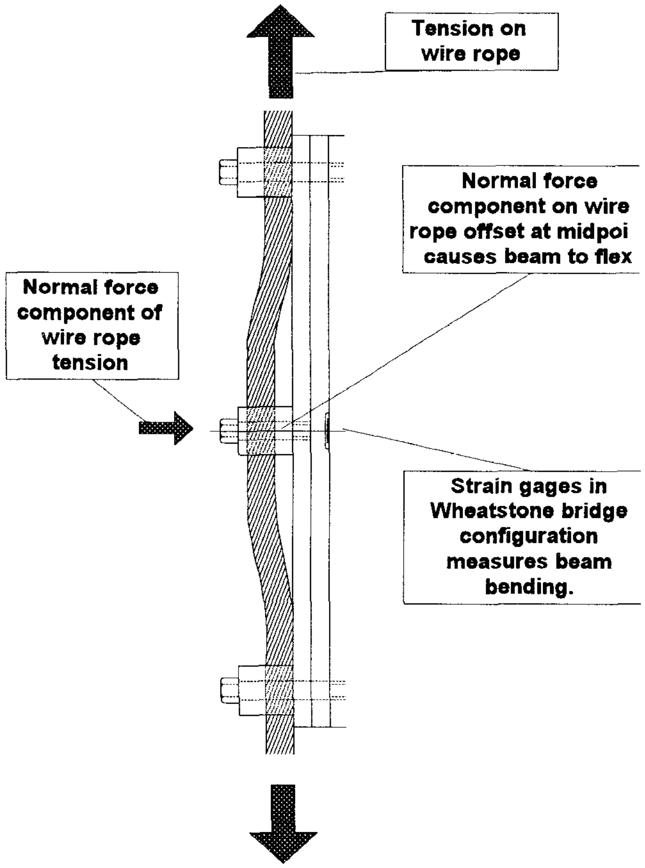

Figure 4.—Concept for wire rope sensor for 3.8-cm (1.5-in) diam wire rope

A conveyance-mounted position sensor eliminates the need to correct the position of the conveyance because of rope stretch. This can be as much as 3 m (10 ft) because of loading and unloading, depending on the conveyance loads and length of wire rope played out. Errors in position may also arise because of aging of the rope, the conveyance becoming stuck, and mechanical slippage or wear in the hoisting machinery.

An off-the-shelf optical encoder was selected for determining position. The encoder was mounted below the guide wheel on an aluminum arm connected to a welded bracket on the conveyance. The encoder shaft is connected to a 30 cm (1 ft) in circumference polyurethane-faced wheel. One revolution of the wheel corresponds to 30 cm (1 ft) of travel on the face of the guide. Grade 60 polyurethane was found to minimize slippage between the wheel and the wooden guides.

Measurement of guide displacement can warn of impending slack and tight rope conditions caused by shaft wall movement. These measurements can also be used as an aid in inspection of shaft guides. A 600-ohm rotary string potentiometer with 25 cm (10 in) of travel measures the distance between the guide rails to 0.1 cm (0.05 in). As the stainless-steel cable extends, it rotates an internal sensor that produces an electrical output proportional to the cable position. The potentiometer is calibrated to obtain a voltage output ver-sus travel distance. It is attached to the encoder bracket and connected across the shaft with a spring-loaded ex-tension tube assembly (figure 3). This tube protects the potentiometer wire and holds the encoder wheel and a dummy wheel on the opposite guide firmly against the face of guides.

B. Signal Processing

A custom-designed data acquisition package was developed for processing the sensor signals and converting data to a format suitable for computer input. The package includes a battery-operated, microcomputer-controlled signal processing board (SPB), a spread-spectrum radio modem, and a 12-V battery. The SPB monitors and processes data from six analog channels and one digital channel and provides optically isolated serial data output. The channels are currently configured for two 12-bit, full-bridge strain gauge channels for load cells, four 8-bit channels for SPB and load cell temperature sensing with thermilinear circuits, battery voltage, and the potentiometer. The SPB is linked to a radio modem for data telemetry from the moving conveyance to the computer in the hoist machinery room. A second RS232 serial port on the SPB transfers data to a portable computer or terminal on the conveyance itself for shaft inspection and maintenance purposes.

Functional operation of the SPB is controlled by a programmable read-only-memory (PROM) chip. The PROM allows a data sampling at a rate of 100 milliseconds, or 9-byte data packets (72 bits) 10 times per second. For a conveyance traveling at 183 m/min or 3.05 m/s (600 ft/min or 10 ft/s), this sampling rate provides data for every 30 cm (1 ft) of conveyance travel. At the completion of each sampling interval, digitized analog sensor information is combined with encoder position data and transferred to the hoist room computer by way of the data link.

Data are transmitted in a serial binary format as 8-bit bytes with the most significant byte first. The 12-bit ana-log sensor input for the load cells transmits information as unsigned 16-bit values. The 8-bit analog channels from the potentiometer and thermistors are transmitted as unsigned 8-bit binary values. An 8-bit unsigned binary number between 1 and 4 identifies the current 8-bit channel. The encoder value is transmitted as an insigned 8-bit value. The PROM on the SPB alternates data acquisition with data packet transmission to prevent radio signals from disrupting the low-level analog sensor inputs.

In addition to the commercially available Wonderware software package used for hoist control, an in-house-developed computer program was written using the Visual C++ programming language. This program displays conveyance weight, wire rope tension, conveyance position, speed, acceleration, guide displacement, battery voltage, and temperature from the conveyance system. Conveyance data are displayed in text boxes and on dial gauges and trend graphs in real time as received from the SPB through the data link. A sensor calibration screen and a hoist and shaft configuration setup screen are also provided. Data integrity is ensured through the use of 2-byte "checksum" in the C++ code and is transmitted as an unsigned 16-bit value in each data packet.

C. Data Link

Three methods commonly considered for a mine shaft data link are inductively coupled cable transmission, leaky feeder cable transmission, and free radiation. Each of these methods has advantages and disadvantages. Inductively coupled links to a wire rope require interfaces with existing cables to be hard-wired. Leaky feeders require installation of additional cabling in the shaft, which is costly and susceptible to damage from falling debris and degradation from exposure to high levels of humidity and a corrosive environment. Free radiation, while susceptible to the limiting effects of signal attenuation, is readily accessible for maintenance and requires relatively little effort and expense to install because no cable is required.

The selection of free radiation as a communications link for this development effort was based upon a number of desirable characteristics, including ease of installation and accessibility for maintenance, ruggedness, reliability, reasonable cost, and commercial availability of components. Rapid advances in wireless data transmission technology promises to allow ever-increasing distances to be attained in underground environments. Other investigators have reported various levels of success with free radiation data links [8-9]. The key parameters appear to be transmission frequency and antenna configuration. The most encouraging results have been reported at a frequency of 2.4 GHz using directional and patch-type antennae.

The transmitter-receiver unit currently being tested at SRC is a commercially available 2.4-GHz, direct-sequence, spread-spectrum, radio frequency modem. The transparent RF modem is capable of half-duplex operation at data rates of 1.2 to 19.2 kbyte/s and has integral voice communication capabilities. Maximum transmission distance in free air is advertised as being in excess of 2 km (1.5 miles) using line of sight and 200 to 300 m (600 to 900 ft) indoors. Transmitter power is 500 mW (27 dBm), and receiver sensitivity is -100 dBm. The conveyance antenna is a plastic-encapsulated YAGI directional antenna. The fixed receiving antenna, mounted at the sheave wheel of the shaft, is a patch type. Antenna gain is 14 dB for each antenna.

5. TEST RESULTS

Field tests are being performed both at the SRC hoist research facility and in a secondary escape shaft of a deep mine in northern Idaho. The purpose of the test series at the research hoist is to validate the functional performance of the sensors and conveyance-mounting schemes and to evaluate conveyance load and rope tension during normal and abnormal hoisting cycles. Figure 5 shows a normal cycle for the 272 kg (600 lb) skip with a 330 kg (780 lb) payload (total weight of 602 kg [1,380 lb]) being hoisted over a distance of 20 m (60 ft). The effects of acceleration loads on the rope tension are clearly seen during the acceleration-deceleration stages at the top and bottom of the cycle. Ascending conveyance acceleration was limited, but deceleration forces were considerably greater at the top because the shorter rope resulted in a stiffer system.

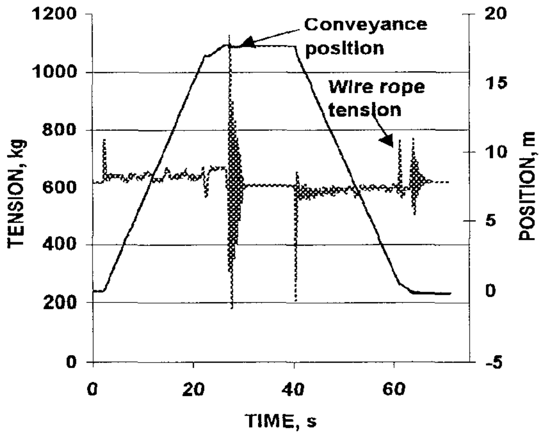

Figure 5.—Normal ascent and descent cycle for skip conveyance.

Rope tensile loads resulting from ascending acceleration exceeded the static tension resulting from the toal weight of the conveyance by about 30%. Deceleration load effects on rope tension at the top of the hoist tower were much greater because of the shorter length of the wire rope, making a much stiffer system. The resulting peak tensile forces in the rope exceeded static load by about 80%. Descending acceleration resulted in unweighting of about 67% of the static load and descending deceleration forces of 22% of static loads.

An abnormal hoist cycle occurs when the conveyance exceeds speed or position limits as defined by the hoist motor controller. The most serious hazard is a tight or slack rope

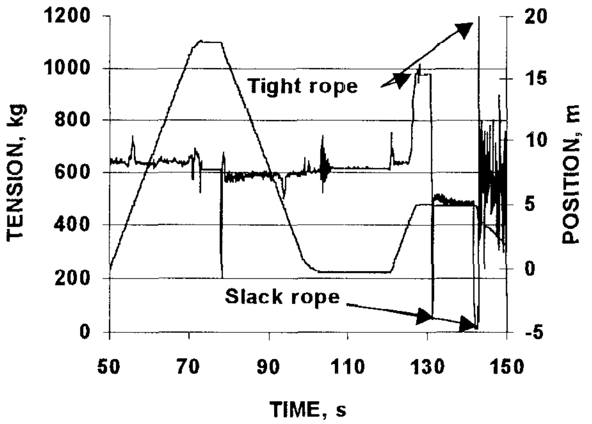

Figure 6.—Simulation of slack and tight rope conditions

condition. Figure 6 shows a simulated slack and tight rope condition resulting from an induced guide displacement. A guide support bracket was disconnected and one guide was displaced into the hoistway by about 1.5 cm (0.5 in) about 6 m (18 ft) from the shaft bottom. This figure shows the initial normal hoisting cycle followed by a cycle in which the conveyance became stuck between the guides because of excessive guide displacement. When the conveyance was stopped by the deformed guides, tight rope conditions resulted in rope tensions of about 60% of the conveyance weight. As the winding drum was reversed, a slack rope condition developed when the conveyance remained static. The conveyance then dropped about 1 m (3 ft), suddenly taking up the slack in the rope and causing another tight rope condition that exceeded conveyance weight by 120%. This was followed by another slack rope occurrence at the skip, which then fell to the bottom.

Several tests were also conducted during normal inspection activities at the escape shaft of a deep mine in northern Idaho. The rectangular shaft is 1,667 m (5,000 ft) deep and has two 1.7-m (5-ft) square hoisting compartments lined with timber lagging. The accuracy of the encoder position sensor and the maximum data transmission range using various modem and antenna configurations were evaluated.

Initial tests were conducted using a 467-MHZ radio modem with omnidirectional antennae. This system provided an effective range in the shaft of only about 300 m (1,000 ft), and significant errors were present in the data because of radio frequency and electromagnetic interference. A data link using a 0.5-W, 2.4-GHz modem with a high-gain directional YAGI antenna on the conveyance and a patch-type antenna at the shaft collar provided the best results. Reliable data transmission from the SPB from a depth of approximately 630 m (1,900 ft) was achieved, as shown by the plot of position data in figure 7. A scheduled stop at the 500-m (1,500-ft) level of the shaft is shown, as is the depth where the data signal was lost on the way down and picked up again on the return trip. The encoder distance indicator was about 33 m (100 ft) less than the actual distance, or 1% less than the 3,000 m (9,000 ft) trip. This discrepancy was because the encoder wheel bounced on the rough spots on the girders. It is also suspected that excessive attenuation of the data signal occurred because of the great amounts of water in the shaft at approximately 630 m (1,900 ft), as well as the wood lining.

These encouraging results, combined with the availability of an ever-broadening range of low-cost, unlicensed, spread-spectrum radio equipment, make wireless data communication the logical choice for a shaft data link. It is anticipated that an effective transmission range of 2,000 m (6,000 ft) is possible with existing technology. Approaches currently being investigated include the use of higher frequency dish receiving antennae.

6. SUMMARY

A state-of-the-art hoisting research facility has been completed. Hoist control is PC-based and uses off-the-shelf software that can be readily retrofitted into existing hoisting systems. The facility and the conveyance monitoring system allow personnel to assess critical hoist operating

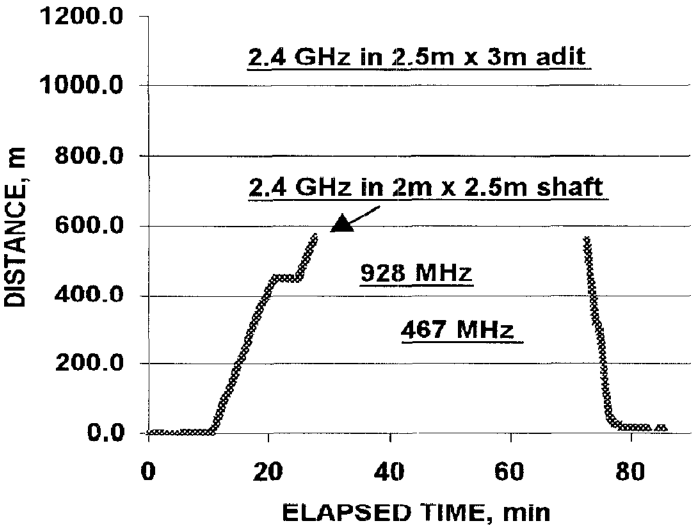

Figure 7.—Wireless data transmission distance for different frequencies (underlined)