Articles

Applying ergonomics to underground coal mining equipment

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The three papers which comprise this special issue of Ergonomics Australia summarise presentations made at a seminar held in Pokolbin NSW on October 17, 2006. The seminar formed part of a research project funded by the Australian Coal Association Research Program (ACARP Project C14016 Reducing injury risks associated with underground coal mining equipment).

The project began in 2004 with an approach from Xstrata Coal NSW for assistance with reducing injuries associated with equipment across the company's underground sites. It became apparent that the issues were not confined to any one company, and a project involving the industry more widely was undertaken between April 2005 and March 2007. The project involved analyses of narratives describing injuries associated with underground equipment, review of relevant literature from international research agencies, and visits by project staff (Robin Burgess-Limerick, Gary Dennis, Suzanne Johnson & Jenny Legge) to 14 Australian underground coal mines. An aim of these visits was to document current best practices in the control of injury risks. Visits were also undertaken to equipment manufacturers in both Australia and the USA. The outcomes of the project include a *Handbook for the Control of Injury Risks Associated with Underground Coal Mining Equipment,* which incorporates the information gathered during the project, regarding risks and controls and contains a generic risk assessment tool. The handbook is available at burgess-limerick.com.

The Pokolbin seminar aimed to communicate the results of the project to industry, and also brought together ergonomists with considerable experience in the area (Barbara McPhee, Justin O'Sullivan, and Lisa Steiner - NIOSH Pittsburgh) to share their views. The seminar also included brief presentations by mine staff and manufacturers, and was attended by 100 people from 8 manufacturers and 15 mines as well as regulators and others. It was a very successful day, particularly in giving the manufacturers motivation and direction for future improvements in equipment design. Much of the information has wider applicability than mining and will be of interest to Ergonomics Australia readers.

1) Equipment Related Issues and Controls in the USA Underground Mining Industry

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While the rate of lost-time injuries in the USA has steadily decreased over the past 10 years (from over 10 per 100 FTE in 1995, to 6 in 2004), underground coal mining remains a hazardous industry (www.cdc.gov/niosh/mining/stats). One of the contributors to this injury risk is working with or near underground coal mining equipment. Roof bolting machines, and to a lesser extent continuous mining machines, have been consistently identified as high risk equipment, collectively accounting for approximately 24% of all injuries to underground coal miners.[1] Load-Haul-Dump vehicles (LHD), shuttle cars (sc) and personnel transport are also associated with injuries in underground coal mines.[2] Continuous mining machines (CMM) consist of a rotating cutting head and a conveyer. The cutting head cuts coal and the conveyor loads and transfers coal. The SC transports the coal away to a conveyer, from where the coal is transported to the surface. After a section of the mine is cut, the CMM is removed and replaced with a bolting machine from which miners drill holes (using drill steels) and place bolts and/or some other type of permanent support in the roof to maintain its integrity. These machines are all electrically powered via a trailing cable. LHD and scoop vehicles are general purpose diesel or battery powered vehicles used for carrying materials, cleaning up mined areas and towing trailers underground. Personnel transport vehicles are predominantly used to transport miners underground.

These injury results are consistent with previous observations[1,3] that roof bolting machines are the equipment most frequently involved in underground mining injuries, and that being struck by rock falling from supported roof as the most common mechanism. The proportion of injuries associated with bolting machines in USA underground coal mines appears to have remained unchanged since the 1970s (cf., 15%, in 1977[4]; 17% in 1989[1]; 16% in 1993[5]; 17% in 2004). Similarly the proportion of injuries associated with continuous miners (8%) is consistent with that previously reported for USA mines (7% in 1989[1]). The total percentage of injuries associated with the equipment considered (37%) is considerably higher than that reported recently for underground coal mines in New South Wales, Australia (23%).[6] The differences may be a consequence of different environmental conditions (higher roof heights in Australian mines) and differences in mining methods (in Australia, bolting is predominantly undertaken by bolters integrated onto continuous mining machines). Perhaps in part as a consequence of the higher roof heights, Australian mines have a much higher prevalence of the use of screen (wire mesh placed to the roof during the bolting process) to prevent minor rock fall injuries.

An analysis of injury narratives for 2004 (MSHA database) suggests the following hazards as the highest priority for elimination or control (see Appendices A, B and C):

- rock falling from supported roof;
- rough road while driving or travelling in LHD/scoop, shuttle cars and personnel transport vehicles;
- collisions while driving LHD/scoop, shuttle cars & personnel transport vehicles;
- inadvertent or incorrect operation of bolting controls; and
- handling continuous miner cable.

The National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory (PRL) located in Pittsburgh, PA, conducts research to reduce injuries, fatalities and illnesses in the mining industry. The facility is equipped with state of the art laboratories and technologies to study root causes and solutions to mining hazards. For each of the above priority problems, a discussion of root causes based on literature and field research will follow, along with the recent research results or, in some cases, a description of ongoing research studies to resolve the hazards.

Rock falling from supported roof

Rock fall data analyses are remarkably consistent with previous data, for example Klishis, Althouse & Stobbe et al(5) analysed 2685 bolting related injury narratives and found that 911 (34%) involved falls of roof material (cf. 33% this report). Similarly, Bise, Masutomi, & Chatterjee(7) determined that in 1987, 57 of 319 continuous miner related injuries (18%) were due to falling rock (cf. 21%, this report). The total number of injuries as a consequence of coal or rock falling from supported roof (477) is reduced from the 650 reported by Robertson, Molinda & Dolinar[8] as the annual average from 1995 to 2001, suggesting that there has been a reduction in overall injuries of this type in recent years. While this reduction reflects the overall reduction in injury rate occurring during this period, it is likely that the change is in part a consequence of the introduction of roof screening in some US mines, which has been demonstrated to virtually eliminate injuries of this type.[9] Indeed, injuries due to rock falling from a supported roof were almost non-existent in a similar analysis of equipment related injury narratives from Australian underground coal mines where screens are routinely put in place during bolting.[6]

While screening is undoubtedly an effective control, the low seam heights in some USA coal mining areas make screen installation difficult. Additional hazards are also introduced with the use of a screen, particularly additional risks of musculoskeletal injury associated with handling the screen, as well as potential exposure to rock fall while setting the screen. However, of 959 Australian equipment related injury narratives, only 27 mentioned a screen,[6] suggesting that the additional risks of injury associated with handling and placing a screen are much less than the risk associated with the rock fall hazard being controlled, at least in the relatively high seam conditions which predominate in Australian mines. Improvements in the handling of a screen are also being developed at mines sites and have potential for further reducing the risk associated with handling and placing a screen.

The importance of preventing rock fall injuries cannot be overstated. Where low seam heights make screening with steel mesh difficult, it may be necessary to develop alternative means of reducing the risk of minor rock falls such as the use of shotcrete or other membrane.[10] Preventing minor rock falls, whether through screening or other means, could prevent nearly 500 injuries per year or 13% of all injuries in US underground coal mines.

One reason mine companies do not screen is due to the extra time and materials cost associated and the possible increased physical effort required. In an effort to encourage mines to increase the use of screens, a study to understand the physical requirements and time costs were conducted for the transporting and installation of roof screens. An intervention consisting of a dual rail mounted to the roof bolting machine was tested to determine its effectiveness in reducing physical effort and time to install. Muscle activity, and motion analysis when using two different lifting techniques (side and overhead) from two different locations (from the floor / while leaning against the rib) for two different seam heights (66” and 84”) were noted.

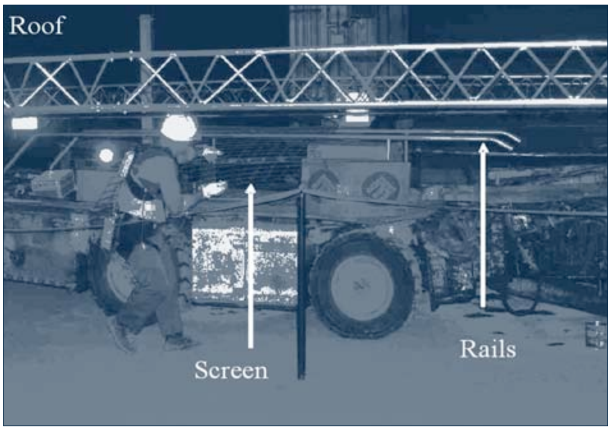

Fig 1. Dual Rail Intervention for Screening

Results showed that less muscle activity was required when the screen was lifted from the leaning rib condition. There was no difference when lifting from the side or overhead. This suggests that storing the materials against the rib would lessen the physical requirements of roof bolter operators. When transporting screens (carrying the screen overhead, to the side or dragging) in both 66" and 84" seam heights, it is not recommended to drag the screen as muscle activity was significantly greater than the other conditions. Muscle activity, using EMG technology and monitored trunk kinematics using the Lumbar Motion Monitor developed at The Ohio State University, was collected to determine effectiveness of screen installation with and without the dual rail intervention.[34] In both seam heights, muscle activity was found to be significantly lower when using the rails. This intervention allows the screen to be glided easily without materials getting "hung up" on the supplies and materials on the roof bolting machine.

This intervention is undergoing small improvements and will be tested further. The specifications will be made available by the end of 2007.

Rough Roads

Injuries associated with driving or travelling in a vehicle that encounters a pot hole or other roadway abnormality accounted for 20% of injuries associated with scoop/LHD, Shuttle car or transport. This is somewhat lower than the 34% of injuries associated with this mechanism in recent Australian data,[6] which may reflect the greater use of rail transport in USA mines. Even so, improvements to roadway standards to avoid potholes and other abnormalities would be an effective means of preventing injuries of this type. Jarring and jolting often caused by these "potholes" or other abnormalities is a major contributor averaging 77% of back, neck and head injuries. Provision of vehicle suspension, and improved seating have potential to reduce these acute injuries.[11,12] Such improvements will also reduce exposure to high amplitude whole body vibration which is strongly associated with the development of back pain through cumulative mechanisms.[13]

Fig 2. NIOSH Design
Mid-Seam Shuttle Car Seat

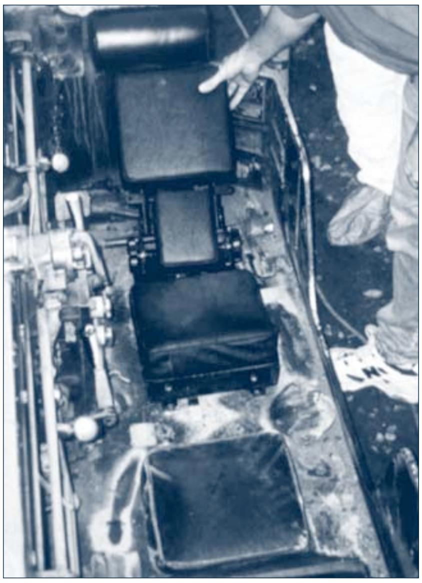

Fig 3. NIOSH Design
Low-Seam Shuttle Car Seat

Laboratory studies of foam padding and seat suspension systems for underground low-seam and mid-seam shuttle car seats were conducted at PRL and at several participating coal mines. Accelerometer data was collected and analyzed both before and after the proposed seats were installed. The NIOSH developed seat with lumbar support was preferred by a large majority of users and quantitative analyses showed a significant reduction in whole body vibration. Joy Mining now includes this improved seat design as part of its product line and independently tested the new design and confirmed the results of the NIOSH study. To date, over 26% of the US low-seam mine shuttle cars are equipped with this new design and a total of over 510 seats have been sold.

Vehicle collisions

While vehicle collisions represented a relatively small proportion (15%) of the injuries associated with Scoop/LHD, Shuttle car and transport, the consequences of collisions are frequently severe, and include fatalities. This figure is also twice the proportion of "collision" related injuries for these vehicles found in recent Australian data.[6] The probability of vehicle collisions is increased considerably by the restricted visibility inherent in LHD and shuttle cars, and this is likely to be exacerbated by the low seam heights in many USA coal mines. This is not a new observation. Reports by Kingsley, Mason & Pethick,[14] then Pethick and Mason[15] described the visibility difficulties associated with the design of free-steered vehicles. Simpson, Rushworth & von Glehn[16] suggested that many underground vehicle collisions are at least in part a consequence of restricted driver visibility. The visibility restrictions while driving LHD vehicles is one of the few aspects of mining equipment design which has been the subject of formal research. The research has largely been limited to documenting the extent of the problem and providing methods for assessing the lack of visibility associated with current designs.[eg.,14,17,18] Recommendations for LHD redesign arising from the research include raising the sitting position where possible and cab redesign to remove visual obstructions. Physical separation of pedestrians and vehicles as far as practicable, and vehicle mounted proximity sensors and cap lamp battery mounted emitters may also be beneficial in preventing potentially serious injuries.

NIOSH PRL has conducted studies of proximity detection systems in an effort to reduce collisions while operating machinery.[19] This system warns operators or other mine workers when they are close to equipment. This magnetic field based system named HASARD (Hazardous Area Signalling and Ranging Device) provides remote alerts or machine shut down functions. The HASARD transmitter signal feeds into a wire loop which projects a uniform magnetic field around the dangerous area or the equipment. A microprocessor in the receiver determines when a local alarm should be activated and when data need to be conveyed over a short-range radio link to enact the alarm and/or shut down the machine. This technology is commercially available. The system has been applied to CMMs, haul trucks and conveyor haulage systems but could be adapted to shuttle

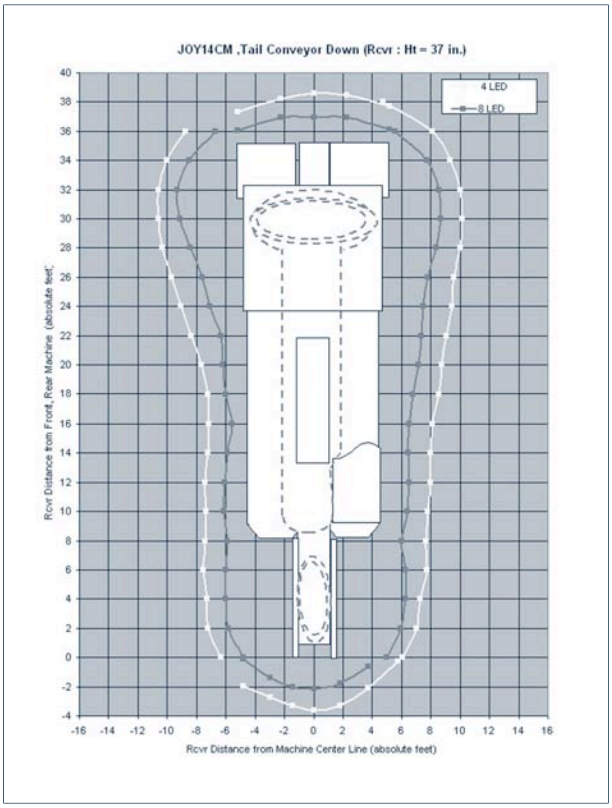

Fig 4. Hazard transmitter detail cars and other underground vehicles.

Inadvertent or incorrect operation of bolting controls

The hazards associated with inadvertent operation of controls, operation of incorrect controls, operating controls in an incorrect direction, or whilst a person is located in a pinch point, have long been recognized. Miller and McLellan[20] commented on the "obvious need" to redesign roof bolting machines, suggesting, for example, that of 759 bolting machine related injuries, 72 involved operating the wrong control, while Helander, Krohn & Curtin[3] determined that 5% of bolting machine accidents were caused by control activation errors.

Improvements to guarding to prevent accidental control operation, standardization of mining equipment controls, especially drilling and bolting controls, and the use of shape and length coding has been suggested on numerous occasions over the past 40 years. [3, 5, 21-27] Hedling and Folley[21] noted (in the context of continuous miner controls) that *the widespread use of traditional round control knobs regardless of function being controlled is another source of error in operation* and proposed that *Each control knob is designed to resemble (at least symbolically) the equipment it represents.*

Similarly, Helander, Conway, and Elliott et al[23] suggested that *poor human factors principles in the design and placement of controls and inappropriately designed workstations contribute to a large percentage of the reported injuries* (p. 18). In particular, a lack of standardization of controls was noted, with more than 25 different control sequences being identified, differences existing even on similar machines produced by same manufacturer. Helander, Conway & Elliott et al also noted the lack of control coding, violation of direction stereotypes, a mixture mirror image and left/right arrangements, and the possibility of inadvertent operation.

Klishis, Althouse & Stobbe et al[5] in 1993 again noted a lack of standardization of bolting machine controls, even among machines from the same manufacturer, and commented on the potential for injuries due to incorrect control operation. In a six week period in 1994, three operators of roof-bolting machines in the USA were killed. Two were crushed between the drill head and machine frame while bolting; the third was crushed between the drill head and canopy. A Coal Mine Safety and Health Roof-Bolting-Machine Committee was formed by MSHA to investigate, and a report released[24] which determined the causes to be the unintentional operation of controls. The solutions proposed in this report were:

1. two-handed fast feed;
2. drill head raise shutoff;
3. auxiliary controls;
4. guarding;
5. pinch point identification;
6. self-centering controls;
7. hands-off drilling;
8. insertion/retrieval devices;
9. standardized control layouts; and
10. pre-operational inspection.

Other suggestions included in this report included:

- provide industry-wide accepted distinct and consistent knob shapes and relative handle lengths to identify corresponding control function.
- standardize machine control lever movement and corresponding machine function movement.

MSHA subsequently called for industry comment on an advance notice of proposed rulemaking titled *Safety standards for the use of roof-bolting machines in underground mines.*[25] that suggested that MSHA was developing design criteria for underground bolting machines. On February 12, 1998 the comment period was extended to March 9, 1998, however no related rule or design criteria were subsequently released. On June 10, 1999, MSHA released a program information bulletin[26] that reported an investigation of a subsequent fatal accident as having *revealed that a potential hazard exists on roof bolting machines with machine controls that are not protected against inadvertent operation.* This bulletin recommended mines:

- relocate controls to a protected position;
- guard controls;
- redesign controls to prevent operation while the operator is in a pinch point; and
- ensure proper storage of supplies and materials to prevent falling on controls.

Analysis of the injury narratives reported to MSHA in 2004 also revealed that the design shortcomings, previously identified as increasing the likelihood of inadvertent and incorrect operation of bolting controls, remain, at least to some extent. Bolting machine controls require guarding to prevent inadvertent operation (while still allowing access for intentional operation). Improvements to bolting machine design are required to guard pinch points and provide interlocks to reduce the probability and consequences of intentional or unintentional control operation whilst the operator or other person is in a hazardous location.

Bolting machine controls also require standardization to an appropriate layout (including shape and length coding) to reduce the probability of operation of the wrong control, although open questions remain regarding whether control layouts should be mirrored, and the relative importance of shape, location and length coding for the prevention of "wrong control" type errors. For example, while Helander, Conway & Elliott et al[23] noted that the mirror arrangement question was controversial and drew on the results of Pigg[28] to conclude that a mirrored control layout was preferable, a contrary recommendation was made by Muldoon, Ruggieri, & Gore et al.[27] Control standardization must also consider carefully the question of directional control response compatibility principles to reduce the probability of operation of controls in the wrong direction. Further research is required to determine the most appropriate layout and directional control-response relationships specific to bolting machines. Chan, Pethick & Collier et al[29] suggested that conflicting recommendations and gaps in the literature would need to be resolved before any standardization of control-response relationships for mining machines was possible. (see also Simpson & Chan [31])

This statement remains true and is the reason for further investigation to clarify the consequences of standardization of controls, control orientation and control response expectations. NIOSH and the University of Queensland along with ACARP (Australian Coal Association Research Program) and in collaboration with roof bolter manufacturers plan to conduct laboratory and field studies to address the inadvertent or incorrect activation of bolter controls issues. The studies will help to determine:

- consequences of mirror versus non-mirrored control layouts on error and reaction time;
- relative importance of location coding, shape coding and length coding;
- relative strengths of direction control-response compatibility relationships in different planes;
- consequences for new operators when using different designs and layouts; and
- consequences for current operators of changing to a new design and/or layout.

These studies will be conducted beginning in April 2007.

In response to the crushing and pinning injuries, regardless of the root cause, NIOSH is currently conducting studies regarding reaction time of operators when operating the vertical boom arm, the swing arm and the tramming functions of the roof bolting machine. These studies have used roof bolter operator reaction times obtained from mock up laboratory studies and then placed into a virtual human simulation package called JACK to determine appendage speeds that would not allow operators to get out of the way. These results are currently being validated and will provide recommendations for maximum speeds for appendage movement.[33]

Cable Handling

The injury narratives suggest that, in 2004, handling cable accounted for 76 of the 283 continuous miner related injuries (27%), somewhat more than the 11% noted previously[7], but consistent with recent Australian data in which 23% of continuous miner related injuries were associated with handling cable.(14) Technological changes over the last 10 years have resulted in longer cuts. It may be speculated that increases in the length of cable being handled, combined with reduction in the number of miner workers and increases in the average age of miners, may in part account for the increased proportion of cable handling injuries.

The severity of injuries associated with handling cable varies from relatively minor shoulder strains to serious back injuries. While the cumulative nature of most musculoskeletal injuries implies that other manual tasks are likely to also have contributed to these injuries, there is no doubt that handling continuous miner cable represents a high risk of injury and is consistent with biomechanical analysis of the task.[30,31] Engineering controls are required to eliminate or reduce manual cable handling. Integration of cable and other services with continuous haulage has been suggested in the context of remote control.[32]

There is a Monorail cable handling system used in Australia for the higher seam conditions developed by Macquarie Manufacturing in Australia; it is a monorail system and has been installed in Centennial Coal's Newstan Mine in New South Wales. This monorail supply system encompasses all services-related equipment from the face area out-by, to the incoming services cut-through. At the face, cables directly interface with the continuous miner, with no detachment required during the tramming process, making it no longer necessary to install or manage cables. The main requirement to use this system is the installation of an easily-managed monorail beam adjacent to the miner, with a series of traction drive units located throughout the system, which provide an integrated means of cable management. Macquarie Manufacturing stated that manual handling of equipment has been reduced significantly when using this monorail system. This system or a similar system may be investigated to be used in the USA and adapted for lower seam conditions. The system is capable of handling cable and could potentially be engineered to move other supplies and materials. This system and other systems are being investigated in both Australia and the USA.[2]

Summary

In general, the 2004 data analysis showed many equipment related issues of which the top priorities are either already being addressed and have preliminary results or are slated for research in the near future. NIOSH is currently addressing issues associated with small falls of rock through the screening studies and the dual rail intervention; rough roads through the whole body vibration studies; and the new shuttle car seat design, and collision with machinery through the HASARD system research. Future studies include the inadvertent and incorrect operation of bolting controls through a joint study with University of Queensland. NIOSH will continue to study these and other issues related to the safety and human factors of machine design to reduce both acute and cumulative type injuries. In addition, research to prevent these issues also points to the need for equipment manufacturers to design for a human interface – to consider the limitations and capabilities of workers when designing. In this effort, NIOSH is planning to provide original equipment manufacturers with the training and education to integrate human factors principles into their design and to their distributors. A new project is planned for 2007 which aims to provide this training for OEMs. It should enhance communication between mining operations and OEMs regarding better equipment design and educated ordering and retrofitting decisions, and thus introduce human interface problem solving techniques.

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