Mineworker fatigue:

A review of what we know and future decisions

by Tim Bauerle, Zoë Dugdale and Gerald Poplin

Fatigue presents several challenges for the mining industry. Depending on the specific occupation, daily work or operational setup on any given mine site, mining jobs can have a fair amount of labor-intensive tasks mixed with monotonous and repetitive duties. Combined with the long working hours and shift-work schedules of mining work, the prevalence of fatigue in mine workers may seem rather unsurprising.

Mining is certainly not alone in facing the challenge of addressing worker fatigue. Indeed, many of the characteristics above mirror the similarities of fatigue in other industries, such as health care, aviation and security. To the extent that fatigue in mining acts like fatigue in any other industry, then any fatigue management applications, trainings, or interventions in existence can be borrowed from other industries and applied to mining in a cookie-cutter approach. However, some have argued that mining in particular is especially susceptible to increases in the prevalence of fatigue beyond the characteristics listed above due to the multifaceted combination of factors in mining environments associated with fatigue: dim lighting; limited visual acuity; hot temperatures; loud noise; highly repetitive, sustained, and monotonous tasks; shiftwork; long work hours; long commute times due to mine site remoteness; early morning awakenings; and generally poor sleep habits (Canadian Centre for Occupational Health and Safety, 2012; Legault, 2011). Legault (2011) in particular argues that it is the combination of these factors simultaneously that can make mineworkers particularly susceptible to sleep deprivation and fatigue in comparison to other industries where these factors are often not present all together. If fatigue looks and acts different in mining, as others have argued, more research is needed to determine if, how, and why worker fatigue might need to be managed differently in mining.

> "It is recommended that the whole fatigue test problem be stated in a form the nature of which may be indicated by the following suggestions: that the term fatigue be absolutely banished from precise scientific discussion, and consequently that attempts to obtain a fatigue test be abandoned."
>
> **Bernard Muscio, Pioneer Australian Philosopher and Industrial Psychologist, in a 1921 Report to the Cambridge Industrial Fatigue Research Board**

While the burden of fatigue on the mining population has not yet been evaluated thoroughly, methods and measures of fatigue management remain a popular point of discussion. Many commercial suppliers and consultancy groups have begun to develop technologically based fatigue monitoring systems (McMillian, 2013). Some technologies can monitor vehicle operators for indicators of wakefulness, such as percent eyelid closure (PERCLOS) and head orientation, while alertness can be monitored at the neurological level using hard hats lined with electroencephalogram (EEG) activity tracking. While such systems could likely offer some utility in addressing fatigue, one criticism of using a stand-alone technology-centric approach is that the technology is usually meant to detect and mitigate worker fatigue that has already occurred and, therefore, does not necessarily prevent or mitigate fatigue from actually happening. Critics argue for a more comprehensive or systems approach that is work-centric and that aims to identify the root cause and outcomes of workplace fatigue. While the U.S. National Institute for Occupational Safety and Health (NIOSH) has previously developed fatigue- and shiftwork-related training materials targeting specific occupations (Centers for Disease Control and Prevention, 2017), no work to date has focused specifically on addressing fatigue in the mining industry by using a comprehensive data-driven approach.

This article aims to concisely review what is and is not known about worker fatigue in mining. To accomplish this, three main research questions are used to frame this review:

1. What is fatigue, and why does it happen?
2. Why are fatigued workers more likely to be injured?
3. What are the most effective ways to reduce worker fatigue?

The basics of worker fatigue

What is fatigue? As a

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concept, worker fatigue is difficult to nail down. This is mostly because fatigue is what researchers call a "latent factor construct," meaning that fatigue is more of an idea that cannot be directly measured but instead must be inferred through several observable characteristics (for a detailed discussion of latent factor modeling, see Everitt, 1984). Adding to its complicated nature, fatigue manifests itself through several different types of characteristics (Shen et al., 2006):

- Psychological (weariness, lack of motivation, stress-induced actions).
- Physiological (loss of strength and stamina, energy consumption).
- Cognitive (slowed reaction time, forgetfulness).
- Behavioral (eyelid closure or head nodding, slower speech, decreased productivity).

Combining these characteristics with the dynamic nature of fatigue itself (i.e., which consists of daily fluctuations) can make fatigue very difficult to assess and manage. Further still, fatigue and sleep are widely studied across a variety of disciplines — epidemiology, internal medicine, neurology, nursing, otolaryngology, pediatrics, psychiatry, psychology, public health, and pulmonology, not to mention somnology, the scientific study of sleep (Altevogt and Colten, 2006) — all of which paradoxically contribute to a rich, conceptual understanding of fatigue, but to little consensus or a clear management strategy. The complexity of fatigue is also reflected in how it is surveyed and reported: fatigue and sleepiness are often hard to distinguish due to self-reported "tiredness" underlying and conflating both symptoms (Shen et al., 2006), and no standard mechanism exists to record fatigue or sleep-related accidents, crashes or injuries (Altevogt and Colten, 2006).

Generally speaking, Frone and Tidwell's (2015) three-factor conceptualization of fatigue is most often referenced by researchers, which states the following (pp. 274–275):

(1) Fatigue involves equal parts of both "extreme tiredness" and "reduced functional capacity;" i.e., fatigue is a subjective feeling that can lead to an objective decrease in performance.

(2) Fatigue can manifest physically, mentally, and/or emotionally; i.e., muscle tiredness, mind "fogginess," emotional exhaustion, etc.

(3) Fatigue is "temporally tied to the workday;" i.e., there is a connection between worker fatigue and the time of day at work.

What is the burden of fatigue? Fatigue is a serious symptom that is prevalent across a variety of occupations and industries (World Health Organization, 1990). The U.S. Centers for Disease Control and Prevention, (CDC, 2015) estimates that one in three adults does not get enough sleep, labeling fatigue as a public health problem. Fatigue has been estimated to put roughly 130 million U.S. workers at risk for an occupational injury (Lombardi et al., 2010) and is estimated to cost the U.S. economy upward of $411 billion annually (Hafner et al., 2016). Working more than 12 hours a day has been associated with a 37 percent increase in injury hazard rates and a 23 percent increase when working more than 60 hours a week (Dembe et al., 2005). Compared to workers who sleep between seven and eight hours a night, workers who sleep less than six hours are at a 1.79 to 2.65 times greater risk for occupational injuries (Lombardi et al., 2010). In this same vein, one meta-analysis aggregating 27 observational studies found that workers with sleep problems had on average a 1.62 times higher risk of being injured, and that approximately 13 percent of work injuries could be attributed to sleep problems (Uehli et al., 2014).

A NIOSH study in the transportation industry found that shorter sleep duration, sleeping soon after the end of a work period, and less sleep between 1 a.m. to 5 a.m. were related to higher rates of unsafe driving behaviors in subsequent work periods, increasing the risk of incurring an adverse event by approximately 1.8 times that of individuals with adequate sleep (i.e., drivers averaging at least eight hours of sleep per night and were asleep between 1 and 5 a.m. for 80 percent of nights) (Chen et al., 2016). Based on this research, long work hours and extended work shifts have been associated with injuries, illnesses and performance detriments (Caruso et al., 2004), and that both work time and travel time (including commute time) have been inversely associated with average sleep duration (Basner et al., 2007).

Why does fatigue happen? Fatigue is the body's response to a depletion of resources required to handle the immediate task at hand. While perhaps overly simplistic, it can be helpful to think of fatigue as a mechanical balance scale, with "things that replenish" on one end and "things that deplete" on the other end. The more weight on one end, the more that needs to be accommodated on the other end. That is to say, the more depleted one is of energy (fatigued), the more resources will be needed to replenish and balance the scale. Further, the types of replenishment needed will depend on the type of fatigue affecting the worker (physical, mental, etc.). What remains to be seen, however, is how much these different items or factors weigh on one side of the scale versus the other, how much the weights differ from person to person, job to job, or task to task and if the type of fatigue (e.g., cognitive, physical, sleepiness, etc.) matters for the type or weight of the factors that replenish. For example, a nap may be an ideal countermeasure for fatigue due to a lack of sleep, but may not appropriately counterbalance mental or emotional fatigue in the same way as a work break or a day off of work.

Some convincing research indicates that in order to manage fatigue, sleep is most effective (Dawson and McCulloch, 2005; Darwent et al. 2015). In their meta-analysis of 152 sleep studies of workers in organizations, Litwiller et al. (2017) attempted to conceptualize the nature of sleep and how it affects the organizational environment. Their analyses of sleep quality and sleep quantity revealed notable correlations, concluding that important differences exist between the quality and quantity of sleep and that sleep quality was more strongly associated with areas of subjective well-being, such as anxiety, general strain, work-family conflict and job satisfaction. Probing the relationship further, Henderson and Horan (2017) found an overall positive correlation between sleep and work performance. This relationship between sleep and work performance was even stronger for studies that looked at sleepiness as opposed to the number of hours slept (Henderson and Horan, 2017). Additionally, in a meta-analysis focusing on cognitive variables, Lim and Dinges (2010) found that short-term sleep loss led to significant differences in speed and accuracy across various cognitive domains.

Why are fatigued workers more likely to be injured? Although there appears to be a wealth of literature suggesting that fatigue and sleepiness are associated with injuries in the workplace, there is also some confusion regarding why fatigue and sleepiness are associated with workplace injuries. Several biomathematical models of fatigue and performance (Mallis et al., 2004) have been developed that use various inputs, such as sleep and work schedules, to predict injury risk. A good deal of these models seem to be at least partially influenced by Borbély's (1982) two-process model of sleep regulation, which attempts to model the timing and intensity of sleep. According to this model, there are two separate biological systems or processes that regulate sleep: circadian rhythms (i.e., a 24-hour internal biological "sleep-clock") and sleep-wake homeostasis (i.e., a mechanism that regulates sleep intensity based on the balance between any given person's amount of time spent awake versus time spent asleep) (Borbély et al., 2016).

This model was adapted by Akerstedt et al. (2004) in their three-process model of alertness, which split Borbély's sleep-wake homeostasis into two separate processes and aimed to predict subjective alertness from circadian influences: time spent awake — expenditure — and time spent asleep — recovery. Finally, along the same lines, Johns (1993) proposed a four-process model of sleep and wakefulness, with two sleep drives (influenced by circadian rhythms and time spent awake) and two wake drives (influenced by REM sleep and cognition). These models get fairly complicated and intricate, but the bottom line appears to be that less sleep (quantity and quality) leads to slower reaction time and, thus, increases the risk for injuries.

While the aforementioned work is meaningful, it does not provide a definitive starting point for explaining the hows and whys behind miner fatigue and workplace injuries. The famous psychology researcher Kurt Lewin once said that, "there is nothing more practical than a good theory" (1952, p. 169), taken to mean that solving real-world problems requires taking informed ideas which may suggest potentially fruitful new avenues of dealing with a situation (Vansteenkiste and Sheldon, 2006). Taken from the field of occupational health psychology, the following are three examples of high-level theories that support and integrate several fatigue-related risk factors, which may suggest avenues for addressing miner fatigue:

Situation awareness. Situation awareness (SA) is a cognitive process that exists in a three-phase hierarchical pattern: perceiving elements in the environment (e.g., there is a boulder in the middle of the road up ahead), comprehension of the current situation based on this perception (e.g., that boulder is a threat to my safety), and projection of future status (e.g., if I slow down or go around the boulder, I could avoid a collision) (Endsley, 1995). Given this, SA may explain fatigue-related injuries where compromised or depleted cognitive ability could lead to a breakdown in any one of these steps (e.g., failure to notice the boulder, identify the boulder as a threat, or how to take corrective action to avoid colliding with the boulder).

Ego depletion. Ego depletion, self-control, or self-regulation all refer to the idea that willpower is inherently depleting from a mental resource viewpoint, that people have only a finite amount of this resource, and that self-control diminishes naturally over time (Baumeister et al., 1998). From this perspective, engaging in safety-related behavior (e.g., taking extra precautions, doing safety checks, conducting equipment inspections, etc.) is an ego-depleting task. If a worker is already in a depleted state (i.e., fatigued), there may not be a sufficient amount of mental resources for the worker to engage in self-regulatory actions and poor decision-making may result. This is somewhat connected to the Conservation of Resources Theory (Hobfoll, 1989), which argues that stress is the result of loss of physical or psychological resources, and that stress is itself resource depleting.

Job demands-resources model. The job demands-resources model (JDR) of worker stress and health asserts that two major categories of job aspects interact to affect work and health outcomes: job demands (e.g., physical, psychological, social or organizational aspects that are associated with certain physical/psychological costs) and job resources (e.g., physical, psychological, social or organizational aspects that are functional to achieving work goals or reducing job demands and their associated costs) (Bakker and Demerouti, 2007). Injury, therefore, could result from too many demands (i.e., complex environmental stimuli and/or physical fatigue) and not enough resources (i.e., opportunities for recovery, sleep).

Worker fatigue in mining

What do we know about worker fatigue in mining? Although the theories presented provide a general and practical framework for how fatigue may lead to injuries and incidents, it appears from the readily available literature that relatively little is known about the hows and whys of worker fatigue in mining from a scientific perspective. The following section is divided into two parts: first, an overview of the available peer-reviewed scientific literature on worker fatigue in mining is presented, followed by a section reviewing various other documents (e.g., reports, secondary data, case studies, industry recommendations, and trade publications) that pertain to worker fatigue in mining.

Empirical research. A review of readily available empirical scientific articles (i.e., research using recorded observations and data analysis), which specifically investigated some aspect of fatigue in a sample of mine workers shows that large differences are apparent among studies regarding study design, research questions and methods used. Although this review demonstrates large differences among study design, research questions and methods used, as one author aptly stated, there is no silver bullet or smoking gun when it comes to a "one-size-fits-all" approach to addressing worker fatigue in mining (Legault, 2011). From Finnish steel mill plants to fly-in-fly-out (FIFO) Australian mining operations to Iranian industrial mineral worker groups, clearly the cultural, logistical, and environmental factors at play are vastly different. It appears that this complexity is further demonstrated in the results, such that most naturalistic observations of shift schedule changes had both positive and negative consequences for workers and were dependent on a number of other factors at play. That being said, some general trends are apparent and are discussed in the subsections that follow.

Days off, time in bed, sleep time, and restful sleep are not the same. Sleep would seem to be a much easier way of determining if a worker is fatigued. Just figuring out on average how much sleep miners get per night, and anything less than the magic number of seven or eight hours means they are fatigued, correct? Suppose we learn that a particular mine worker went to bed at 9 p.m. and awoke at 4 a.m. We might notate this as the mine worker having received seven hours of sleep recovery. However, suppose we also learn that the worker woke up three or four times during the night and got out of bed each time for approximately 30 minutes. Is seven hours of sleep still a fair number to use, or would five hours be more accurate? Scenarios such as this show why sleep researchers have multiple ways of dividing up hours slept to determine actual recovery time (see Reed and Sacco, 2016, for an overview):

- Time-in-bed (TIB).
- Total sleep time (TST).
- Sleep efficiency (SE; i.e., usually some ratio of TST vs. TIB).
- Duration of sleep episode (DSE).
- Sleep onset latency (SOL; i.e., time between full wakefulness and sleep).
- Wake after sleep onset (WASO; i.e., time awake after initial sleep onset but before the final awakening).
- Time attempting to sleep after final awakening (TASAFA).
- Ratio of sleep time spent in rapid-eye-movement (REM) sleep stage to

nonrapid-eye-movement (NREM) stages.

While it may not be necessary or advisable to track each of these factors for any given sleep or fatigue monitoring system, it is important to understand the general differences between these concepts as sleep is the main recovery method for fatigue. Additionally, some research on mining populations suggests that mine workers may have poorer sleep quality and less sleep efficiency compared to age-matched norms, with around 40 to 60 minutes less of TIB and TST prior to starting a day shift (Legault et al., 2017).

As in other industries, mine worker sleep deficit appears to result in negative cognitive outcomes. A good deal of the literature included in this section assessed reaction time using the Psychomotor Vigilance Test (PVT), which assesses reaction time continuously over a five- or 10-minute period, and reaction time has been shown to be affected by sleep loss in lab studies. In general, some of the studies we reviewed demonstrated substantively slower reaction times near the end of the shift, especially across consecutive work days, which was even more pronounced for night shift workers (Ferguson et al., 2011; Legault et al., 2017; Muller et al., 2008). Of particular note, Muller et al. (2008) looked at reaction times in miners working consecutive 12-hour shifts (10 consecutive day shifts, five days off, eight consecutive night shifts, five days off, etc.), and how reaction times of these miners compared to the reaction times of participants with a blood alcohol level of 0.05 percent. They found that day-shift workers achieved this poorer level of reaction time after eight consecutive shifts (i.e., with two shifts left in current rotation), while night-shift workers reached this level after four consecutive shifts (i.e., with four shifts left in current rotation).

Along these lines, researchers reviewed 263 safety incidents from Australian surface and underground operations and, after using a standardization classification procedure, concluded that incidents due to “skill-based errors” (i.e., error in an operator’s execution of a routine task) were almost four times more likely to involve an operator who had an “adverse physiological state” (i.e., fatigue, illness, etc.) (Lenne et al., 2012).

Mine workers seem generally resilient and can adapt, but resiliency has its limits. Many of the studies featured an assessment of miners before and after the implementation of a shift schedule change to determine the effect on sleep and fatigue (Brake and Bates, 2001; Duchon et al., 1997; Hossain et al., 2004; Rosa et al., 1996). Generally speaking, it appeared that most of these transitions occurred with relatively little incident and on average, workers were able to adapt and self-regulate to their new conditions. As an example of this self-regulation in action, miners stationed in hot areas, compared to miners working in cool underground locations, showed relatively large spikes in physical fatigue during the first half of their shifts and thereafter engaged in self-regulation to manage this fatigue by slowing down their work pace, thereby lowering heart rate and fatigue levels for the remainder of their shifts (Brake and Bates, 2001).

However, such resiliency appears to have its limits. For example, in a 2009 study using U.S. Mine Safety and Health Administration (MSHA) and Bureau of Labor Statistics (BLS) data, researchers were able to determine the independent effects of fatigue caused by Daylight Savings Time on underground mine worker injuries (Barnes and Wagner, 2009). Results indicated that, while the Monday after Daylight Savings Time resulted in only a 40-minute average sleep deficit, this deficit led to on average 3.6 more injuries and 2,600 more days lost due to injuries on that Monday compared to any other calendar day of the year. Two things about this study are worth noting. First, using a sample exclusively of underground miners, the authors argued that they were able to parse out any effects that actual exposure to daylight had on these trends, strengthening their argument that this 40-minute sleep deficit increased worker fatigue, and therefore increased injury frequency and severity. Second, a mere 40-minute sleep difference was sufficient to observe such a substantive increase in average injury frequency and severity (as measured by average days lost per injury). This is somewhat concerning, given that anecdotally it is fairly easy to lose less than an hour of sleep on any given night.

Creating opportunities for recovery appears important. Despite these limits on resiliency, creating ways in which mine workers can adequately recover appears to be important for counteracting the negative effects of fatigue. Total sleep time (TST) was overall higher on days off regardless of shift type in one study (Paech et al., 2010), indicating the importance of using non-work time to recover. One way to do this, as some have argued, is to improve on-site lodging (Duchon et al., 1997). However, others warn that eliminating the need to commute does not necessarily translate into more sleep.

Reduced pressure on nonwork time appears not to have converted into a predicted increase in total sleep time…the current findings suggest therefore that live-in camp environments are not, in and of themselves, conducive to increased total sleep time during each non-work period (Ferguson et al., 2010, p. 73)

Others found that, while a "forward shift rotation" (i.e., day shift, off, afternoon shift, off, night shift, off, etc.) seemed to be superior for sleep quality than backward rotations. Longer shift hours and more continuous shift days per shift cycle were particularly detrimental to the sleep of those rotating on to night shift (Hossain et al., 2004).

Nonempirical research (inferred data, case studies, recommendations)

While the precise burden of fatigue on the mining industry has not been specifically evaluated (i.e., beyond anecdotal evidence), there are some data suggesting that fatigue may be a particular issue for mine workers. For example, the mining industry continues to lead other industries in average weekly hours worked (BLS, 2017), specifically working an average of 45.8 hours per week in 2015 (BLS, 2016). This is at least four to five hours more on average per week than the construction, logging, and oil and gas industries. Workers in the mining industry also have, on average, the longest commutes of nearly any other industry (American Community Survey, 2014). According to MSHA data (2016), for all active mines with >20 employees (n=1,583), 50.2 percent of operations used shifts longer than eight hours (81,534 employees), and 18.2 percent had shifts longer than 10 hours (47,580 employees). Undergroud metal mines were observed to most frequently employ shifts longer than 10 hours (57.6 percent of operations relating to 3,912 employees).

As a case study in this burden of fatigue, Locke (2014) reports that, in the coal mine areas of central Queensland in the Bowen Basin, it is common for some of the mine sites to arrange four consecutive 12-hour shifts, with workers having to commute 300 km (186 miles) each way after every shift. Assuming an average speed of 90 kph (~56 mph), this would equate to a 3-hour and 20-minute commute each way.This leaves a measly 5 hours and 20 minutes for any pre- and post-work activities, childcare, home maintenance, leisure time and perhaps most importantly, sleep.

In trying to address this burden, several solutions and recommendations have been proposed. More than a decade ago, several human factors researchers in mining attempted to have mining subject matter experts rate and rank various aspects of fatigue management technologies (FMTs) to determine what features these technologies should have under ideal conditions. Results from these ratings and rankings demonstrated that, overall, experts recommend that FMTs should ideally contain features such as: the ability to process multiple inputs, use several methods of alerting operators/supervisors/dispatch, mining field validation, individual user customization, and rely on relatively little input from the user (Edwards et al., 2007). Taking a low-tech approach, Eiter et al. (2014) in their case study conducted an applied human factors systems assessment of fatigue risk at a surface mine and saw successful improvement after some minor work schedule changes and widening of haul truck routes.

While not necessarily evidence-backed, several sources have provided recommended best practices for mining fatigue management systems. On an individual (i.e., non-organizational) level, Locke (2014) has listed several recommendations for managing fatigue:

- Obtain at least seven hours of sleep per day over 24 hours.
- After a night shift, avoid exposure to bright light (e.g. wear sunglasses, stay indoors).
- Avoid alcohol and caffeine prior to sleep, as these can disrupt subsequent sleep.
- Keep the bedroom dark, quiet and cool to facilitate sleep.
- Begin recovery sleep as soon as practically possible after a night shift.
- Take a 30-minute to two-hour nap prior to night shift to supplement the main sleep period.

On a more operational level, in a review of the New South Wales mine safety recommendations, several suggestions for mine shift scheduling were created (Wran and McClelland, 2005) as follows:

Maximum of:
- 14 working hours per 24-hour period.
- 60 hours of weekly working time.
- 48 hours of weekly working time averaged per year.

Minimum of:
- One, 24-hour continuous period of rest per week.
- 30-minute breaks every 5.5 hours.

Finally, beyond shift-scheduling

recommendations, several reports voice recommendations based on other organizational and systems factors. Specifically, Idea (2007) argues that any fatigue risk management program should recognize that fatigue is a natural consequence of the long, laborious work inherent in mining and therefore should avoid shifting 100 percent of the responsibility of fatigue management entirely on the individual worker:

“More effective approaches to fatigue management that recognize the responsibilities of employers, as well as employees, have benefits broader than just [Occupational Health and Safety]. The potential of more family-friendly working arrangements to aid the recruitment and retention of skilled workers at a time of serious labour shortages [is] well recognized... [We recommend that] industry should adopt a ‘no blame’ approach to reporting fatigue, responding to reports by addressing work-related causes not by penalizing tired workers.

Along these lines, Hutchinson (2014) too advocated for a systems approach to fatigue management:

“Although procedures and policies to promote fatigue management [are] central, it is absolutely critical we instill the right mind set and embed positive safety behaviors and attitudes in regards to fatigue management throughout our organizations. This should include an open and just reporting system for fatigue hazards, prompt feedback from management; and worker flexibility and ownership for safety.”

What are the most effective ways to reduce worker fatigue in mining? Future directions and conclusions

In short, the current state of knowledge for addressing fatigue in mining is relatively unclear. Few studies have attempted to address the complex nature of fatigue in complex and dynamic work such as mining. A helpful model or theory that represents this idea is Reason’s (1990) accident causation model, or more commonly referred to as the “swiss cheese model.” In the model, any given organization’s preventative mechanisms or controls designed to counteract adverse events (e.g., incidents, injury, etc.) in the workplace are represented as slices of Swiss cheese. The holes in each cheese slice represent varying weaknesses in any given control. The general idea of the model is that a weakness in one system can at times be compensated or covered by the provisions in another system or control, but opportunities for adverse events occur when a weakness of each control are sequentially exploited, i.e., the holes in the layers of Swiss cheese align. In this sense, the model is used to highlight errors or weaknesses on a systems level and if additional controls or interventions are needed between any two layers to account for potential flaw alignment. For a mining example, low tire thread on any given vehicle may not by itself cause any particular incident to occur in an otherwise safe environment. However, if we add in high-volume traffic, rainy weather conditions, and a distracted driver to this scenario, these factors may synergistically combine to create a scenario ideal for an incident to occur (Circadian Technologies, 2014).

Despite the complexity and uncertainty regarding addressing mine worker fatigue, there are fruitful opportunities based on the current review that could create exciting avenues for future research aimed at advancing knowledge on this ambiguous issue, while at the same time develop real solutions that can aid industry in improving fatigue-related issues.

Systematic review of broader scientific literature. Our review earlier represents a short, brief overview of readily available literature on worker fatigue in mining which, as we found, appears somewhat limited. One opportunity here is a “deeper dive” that looks at worker fatigue in mining and other similar industries to provide more specific and targeted answers to the three questions we posed earlier in our introduction. Such a review could aid in creating a working model or theory of mine worker fatigue, where the theories presented earlier are compared against the wealth of scientific evidence from other similar tasks, jobs or industries. From here, common sources and outcomes of mine worker fatigue could be identified and investigated in tandem, while using associations between sources and outcomes to propose potential intervention strategies.

Assessing fatigue interventions. As with most health and safety interventions, a one-size-fits-all approach is likely not feasible nor recommended, especially for a complex industry like mining that maintains a wide range of environments, workers, jobs and tasks. Therefore, there is a need to understand how effective specific interventions for managing mine worker fatigue may be under different working conditions, and if the effectiveness of these interventions depends on the type of fatigue, the type of mine, and the individual differences from worker to worker. Furthermore, obtaining an understanding of the differences among interventions with regard to start-up costs, technological needs, and return on investment would be especially beneficial for smaller or more resource-limited operations. While the Edwards et al. (2007) study represents a well-designed method meant to solicit expert opinion on fatigue-monitoring features, much of the technological landscape has changed substantially in the past 10 years, and an update may be required.

Looking beyond sleep and physical work. In a systematic review of 24 studies on the role of the work environment in worker sleep quality, results indicated that social support at work, job control and organizational justice were related to fewer sleep disturbances, while high work demands, job strain, bullying and effort-reward imbalance were related to more sleep disturbances (Linton et al., 2015). While most research discussed in the current review treats lack of sleep and fatigue nearly synonymously, it is dangerously erroneous to conclude that more sleep by itself with no other investigation into other contributing factors will prevent fatigue in all circumstances. Extraneous factors in mining that may contribute to fatigue or recovery — such as leadership, safety culture, reporting systems, work/life balance, commuting time and opportunities for recovery — should also be studied. The health and safety of workers extend beyond the physical work environment. Investigating how factors such as the social work environment, safety culture, and work/life balance contribute to or mitigate fatigue — in concert with more comprehensive knowledge of the relationships between sleep quality/quantity, physical exertion, and mine worker fatigue — would make for excellent opportunities in better understanding fatigue in mining. As mentioned above in the recommendations by Idea (2007) and Hutchinson (2014), fatigue is likely a systems issue, and the various levels of the work system in mining should be evaluated for how each level independently or interactively contributes to mine worker fatigue.

To conclude, while much is not known about the specific nature or extent of mine worker fatigue, the current review suggests potential paths forward based on what is known about fatigue in general and in consideration of common conditions and contributing factors prevalent in mining. These opportunities have the potential to begin to characterize the complexities of fatigue in mining and hope to offer support aimed at improving the health and safety of the mine workers.

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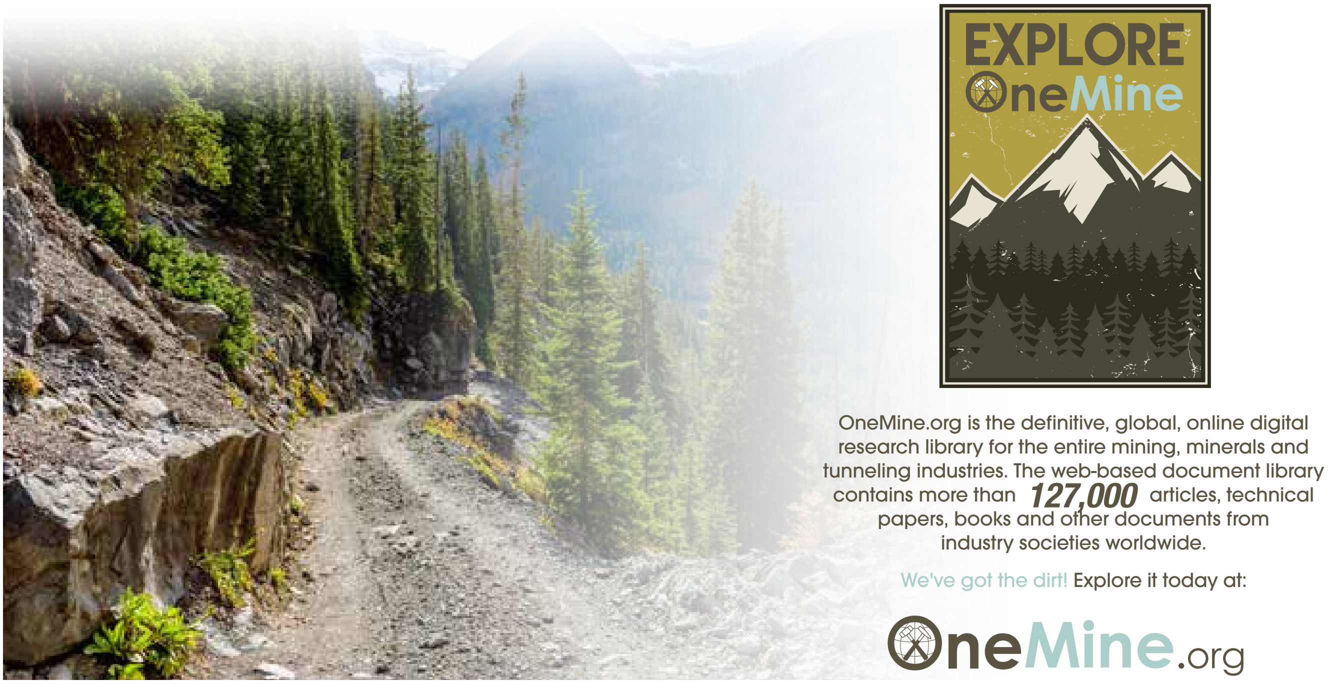

March 2018
Volume 70   Issue 3

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