DEVELOPMENT OF AN EXTENDED SHIFT EXPOSURE LIMIT ADJUSTMENT FACTOR FOR COAL MINE DUSTS

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SUMMARY

Implementation of unusual, or greater than eight hour shifts, places workers at increased risk of exceeding recommended levels of airborne contaminants. This increased exposure places greater stress on the body's ability to cope efficiently and effectively with toxins. Longer work shifts and therefore shorter recovery times between exposure might, in some cases, stress the normal mechanisms to a state where acute cellular damage may occur. Adherence to exposure standards, as well as work methods aimed at reducing dust exposure in the workplace, contribute greatly to minimising the risk of adverse health effects to the worker. It is thus important that extended shift rosters do not allow personnel to be exposed to levels of contaminants in excess of exposure standards.

Several mathematical models have been proposed for adjusting exposure standards for use during altered work shifts. These models include:

- the absorbed dose adjustment model;
- the Brief and Scala model;
- the US Occupational Safety and Health Administration (OSHA) model;
- the pharmacokinetic models of Hickey and Reist and of Stan Roach.

These are all valid methods for adjusting exposure standards with the main difference being the degree of conservatism of each model. This study aims to select the most appropriate model, if any, for the adjustment of coal mine dusts exposure standards.

It is recommended that the pharmacokinetic models be used to calculate adjustment factors for exposure standards and that for simplicity this be reduced to calculation of the ratio of the normal weekly hours exposed to the average weekly hours exposed in the special cycle.

INTRODUCTION

This report reviews four models capable of adjusting exposure standards for use during altered work shifts. In the process of review, both Australian and International literature, have been extensively researched to determine the most suitable model for use in the Australian coal mine environment.

COAL MINE DUSTS

The most significant toxins with regard to dust exposure in coal mines are coal dust and quartz, a form of crystalline silica.

The most prevalent health risk to the worker from coal dust is the development of coal workers pneumoconiosis.
The International Agency for Research on Cancer evaluated coal dust as follows:

> *Coal dust cannot be classified as to its carcinogenicity to humans (Group 3) (International Agency for Research on Cancer, 1996).*

The American Conference of Governmental Industrial Hygienists (ACGIH) intends to reclassify coal dust from an A4 (not classifiable as a carcinogen) (American Conference of Governmental Industrial Hygienists, 1997) to an A2 (confirmed animal, suspect human) carcinogen and to change the coal dust TLV from 2 mg/m^3 (American Conference of Governmental Industrial Hygienists, 1997) to 0.9 mg/m^3 for bituminous coal and 0.4 mg/m^3 for anthracite (Chemical Substances Threshold Limit Values Committee, 1998).

Quartz (crystalline silica - SiO_2) can cause a form of pneumoconiosis known as silicosis on excessive prolonged exposure. Continued exposure to such fibrogenic dusts causes irreversible damage to the lung tissue and a consequent reduction in lung function which can lead to diseases of the cardiovascular system.

The International Agency for Research on Cancer evaluated silica as follows:

> *Crystalline silica inhaled in the form of quartz or cristobalite from occupational sources is carcinogenic to humans (Group 1) (International Agency for Research on Cancer, 1996).*

The American Conference of Governmental Industrial Hygienists (ACGIH) intends to reclassify quartz as an A2 (confirmed animal, suspect human) carcinogen (Chemical Substances Threshold Limit Values Committee, 1998).

The eight-hour time-weighted-average exposure standards for coal dust (containing < 5% quartz) and quartz are 3.0 mg/m^3 (Worksafe Australia, 1995) and 0.2 mg/m^3 (Worksafe Australia, 1996).

EXTENDED SHIFT EXPOSURE STANDARD ADJUSTMENT

Twelve hour shift rosters have been implemented at a number of coal and metalliferous mines throughout Queensland (see Table 1) and New South Wales. Unusual, or greater than eight hour shifts, may place the worker at greater risk of exceeding the recommended levels of airborne contaminants as defined by the Worksafe Australia (1995). Increased exposure places greater stress on the body's ability to cope efficiently and effectively with any toxins. Longer work shifts and therefore shorter recovery times between exposure might, in some cases, stress the normal mechanisms to a state where acute cellular damage may occur (Paustenbach 1985). Adherence to an exposure standard for eight hour or longer shifts assists in minimising the risk of adverse health effects to the worker.

Queensland mines working twelve hour shift rosters:
Coal:
Moura
Collinsville
Burton Downs
South Walker Creek
North Goonyella (underground)
Ensham
Alliance
Metalliferous:
Cannington
Osborne
Selwyn
Thalanga
Kidston
Mount Leyshon
Red Dome

Table 1
Queensland Mines Working 12-hour Shifts

The shift rosters used by these mines vary. Two examples of 12-hour shift rosters are studied for the purposes of this paper. These are a four on/four off 15 week 56 shift roster and a 4 week 14 shift roster. The latter cycle is as follows: 3 night shifts, 4 off, 3 day shifts, 1 off, 2 night shifts, 5 off, 2 day shifts, 1 off, 2 night shifts, 5 off, 2 day shifts, and 1 off.

It has been well established that biological response to inhaled substances is a function not only of concentration and exposure time, but of uptake characteristics. Thus models for adjustment of exposure standards must account for all three parameters. In addition each person's susceptibility to stressors is dependent on many factors which are unique to that individual. The aim of models designed to adjust exposure standards should thus be to ensure that individuals are afforded at least a level of protection equivalent to that provided by the standard eight hour exposure standards.

Several mathematical models have been proposed for adjusting exposure standards for use during altered work shifts. Five of these models have been selected for discussion in this study.

These models are:

- the absorbed dose adjustment model;
- the Brief and Scala model;
- the US Occupational Safety and Health Administration (OSHA) model;
- the pharmacokinetic model of Hickey and Reist;
- the pharmacokinetic model of Stan Roach.

These are all valid methods for adjusting exposure standards with the main difference being the degree of conservatism for each. Three of these models have been selected as they are cited by Worksafe Australia (Exposure Standards Expert Working Group, 1996) and the Roach model was selected as some of Roach's papers discuss the biological half life of mineral dusts.

EXPOSURE STANDARD ADJUSTMENT MODELS

Absorbed Dose Adjustment Model

The absorbed dose adjustment model is a very simple application based on using the estimated ventilation rate to estimate the amount of a chemical that is absorbed during the workshift at the eight hour exposure standard.

The allowable exposure level for an extended shift is then calculated using the absorbed dose over eight hours and simplifies to the ratio of the normal shift exposure standard to the special shift exposure standard being equal to the ratio of the normal shift time to the special shift time.

This equates to an adjustment factor of 0.66 for a twelve hour shift.

Brief and Scala Model

Brief and Scala (1995) developed a model for the adjustment of exposure standards for systemic toxins. They called attention to the fact that for extended shifts exposure time was increased and recovery time between shifts was decreased. For example going from an eight-hour shift regime to a 12 hour workday increases the exposure to toxicants by 50% while the recovery period between exposures is shortened by 25%.

The Brief and Scala model does not consider the biological half life of the chemical or the process by which the body removes the chemical or its metabolites. A limitation of this model is that the calculated reduction factor is the same for all chemicals and only varies with the number of hours of exposure. Pharmacokinetics in terms of half life vary from chemical to chemical thus the Brief and Scala adjustment factor may be too restrictive for many chemicals. A minimum reduction factor for one chemical may be considered excessive for another substance.

The Brief and Scala model is based on the number of hours worked per 24 hour day and the period of time between exposures. It should not be used for 24 hour exposures or work schedules where exposure is less than seven to eight hours per day. It is intended to ensure that the daily dose of the toxicant under an altered work shift is below that for a conventional shift to take account of the lessened time for elimination.

The Brief and Scala formula requires the number of hours worked per 24 hour day and the current exposure standard of the substance under review. No specific knowledge with respect to toxicology of the substance is required. The model does not account for cumulative hours worked over a time frame greater than one 24 hour period, for example it does not allow for the fact that under some extended shift regimes the total time at work is equal to or less than the normal 8-hour day, 5-day week. Brief and Scala is generally considered a conservative model.

As mineral dusts associated with coal mines are not systemic toxins the Brief and Scala model should not be applied to coal mine dusts.

OSHA Model

The basis for the OSHA model is the assumption that the intensity of a toxic response is a function of the concentration that reaches the site of action. This may not be true for irritants, sensitisers and carcinogens but it holds for systemic toxins and for chronic lung disease, e.g. silicosis, commonly caused by mineral dusts.

The rationale behind this formula is that if the amount of a contaminant absorbed on the special (or extended) shift is equal to that which would be absorbed on an eight hour shift, then protection is the same for both groups of workers.

For chemicals which cause an acute response, the daily uptake (concentration *times* time) for a long work shift must be no greater than the daily uptake for an eight hour shift. For chemicals with cumulative effects (those with a long half-life) the adjustment model is based on the dose imparted through weekly exposure relative to the normal 40 hour week rather than the eight hour work day.

Chemicals are assigned a *Health Code Number* which describes the general health effect and are divided into six different categories dependent on the primary type of health effect to be prevented, the biological half life (if known) and the rationale for the exposure limit. The specific health effect of the chemical is also specified. Depending on the type of toxic effect, an appropriate adjustment procedure (including no adjustment) is selected and applied to the substance's exposure limit.

Quartz and coal dust are assigned:

> *Health Code Number 10 (Respiratory effects other than irritation - Cumulative lung damage);*
> specific *Health Effect pneumoconiosis;* and
> *Work Category 3 - Cumulative Toxicity Standards* and *Adjustment Criteria - Exposed-40hr/week* (Paustenbach, 1985).

Worksafe Australia (Exposure Standards Expert Working Group, 1996) does not recommend the OSHA Model as it relies on a substance categorisation system and exposure standards designed specifically for use in the United States. This model may have some application in Australia as many of the Australian exposure standards are based on the same criteria upon which many of the

US standards are based, that is the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs). The coal dust and quartz standards in use in the US do however differ from the Australian exposure standards for these substances.

Pharmacokinetic Models

A key aspect of standard setting is the consideration of the elimination of a toxin from the body. The rate of elimination can be defined by the term, biological half life. The biological half life of a chemical is defined as the time needed to eliminate 50% of the absorbed material; either as the parent compound or one of its metabolites.

Mineral dusts, such as coal dust and quartz, have a biological half life greater than 1000 hours (Roach 1992) and therefore elimination from the body is slow. This characteristic is likely to cause an increase in body/organ concentrations when exposure periods are extended beyond the eight hour, five day week (Guerrini, Flippich and Bourne, 1996).

The biological half life and exposure regime (time exposed and recovery time) are the two factors which determine the degree of adjustment needed to provide an acceptable exposure standard (Paustenbach, 1985). Dependent on the toxicological characteristics of a chemical the extension of time beyond the normal eight hour working day may pose more of a problem than the number of shifts worked per week. This is the case for acute toxins, those with a short biological half life. For substances with long half lives and chronic health effects it is expected that the overall increase in hours worked per week, month or work cycle will have a greater impact on potential health problems than hours worked per individual shift.

The exposure standards represent conditions under which it is believed that nearly all workers may be exposed without suffering adverse health implications. It is thus expected that exposure to a substance at the exposure standard will result in some body burden of the substance in a particular target organ or in the body as a whole and that the body will cope with this level of contaminant. Therefore it would seem prudent and logical to adjust exposure standards such that this body burden is not exceeded.

The adjustment of exposure standards in accordance with pharmacokinetic models is based on this fundamental assumption that a body burden results from exposure at the exposure standard and that this body burden is acceptable for most workers.

Pharmacokinetics dictates that a chemical will be absorbed, distributed and metabolised following an exposure resulting in an increased body burden. The body will then excrete the chemical thus lowering body burden. If exposure is cyclical this process will repeat. If the substance has a long half life not all the chemical will be excreted by the start of the next exposure period and thus it will accumulate. It may be expected that for substances with extremely long half lives the body burden never returns to zero and each successive dose adds to the burden. However for any chemical a steady-state tissue level of contaminant will be achieved (Paustenbach, 1985, p. 133). This is the case for gases and vapours but may not be expected to hold for particulates. However researchers have postulated that clearance of particulates conforms to the first-order kinetics as do gases and vapours (Paustenbach, 1985, p. 235).

Body burden may be viewed as either peak body burden, average body burden or residual (that remaining at the start of the week following exposure) body burden. It is generally accepted that the peak body burden is more likely to predict the occurrence of a toxic effect and thus the adjustment models focus on ensuring the peak body burden for an eight-hour shift regime is not exceeded for an extended shift regime. Residual body burden goes to virtually zero for most chemicals after a weekend away from exposure, though this may not hold true for chemicals with extremely long half lives such as mineral dusts. Regardless, modelling to control this criterion would not prevent excessive peak burdens. The use of average body burden would allow high tissue burdens to occur for long periods even though the time-weighted average body burden may be acceptable.

Peak burden may not be appropriate when the goal of an exposure limit is to avoid a carcinogenic hazard. It is assumed that the "long-term" average dose is more important is assessing risk from carcinogens than day to day peak concentrations (Patty Volume 3A, 2nd Edition, p. 242). Therefore control of the average body burden is important and this is done by limiting exposure in proportion to extra hours worked on a special shift roster over months or weeks.

There are several different pharmacokinetic models which take into account the expected behaviour of the hazardous substance in the body based on knowledge of the properties of the substance. They also consider the number of hours worked each day and week. The formulae require a knowledge of the substance's biological half-life. The model enables a correction factor to be determined which is then applied to the eight-hour exposure standard. If the substance's biological half life is unknown then the worst case reduction factor is used. This model can determine when a reduction in factor is not necessary.

Most pharmacokinetic models, including the Hickey and Reist model and the Roach model, simplify the body to a one compartment system and assume exponential accumulation and decay. The body is viewed as a single homogeneous box with a fixed volume and chemicals are assumed to decay in accordance with a half life and this half life stays constant no matter what the exposure regime. As such a chemical entering the body is assumed to be instantaneously distributed throughout the body and the concentrations in all parts of the body rise and fall in parallel as the chemical is added and eliminated. This assumption holds for particulates whose primary target organ is the lung as the lung acts as the single compartment.

The pharmacokinetic models are less conservative than the Brief and Scala or OSHA models, usually recommending less reduction of the established exposure limit. Whereas pharmacokinetic models are theoretically more exact than the simpler models, their lack of conservatism may not allow adequately for the unknown adverse effects on the body from night work or extended shifts that might affect how well the body metabolises and eliminates a substance. That is they assume that the body's pharmacokinetics in terms of absorption, distribution, metabolism and excretion are not altered by work schedules that differ from the normal eight-hour, five-day week.

When considering substances with very long half lives the adjustment factor is approximately proportional to the ratio of the number of hours exposed in the work cycle to the normal work hours in the cycle.

Pharmacokinetic Model of Hickey and Reist

The pharmacokinetic models are based on ensuring that peak body burden for a special shift roster, such as a twelve hour shift roster, is equal to the peak body burden for the normal eight hour shift roster.

Pharmacokinetic Model of Stan Roach

This model was considered by Roach to be more realistic than the conservative approach of Brief and Scala. Roach suggested that the exposure standard for substances with long half lives be modified in proportion to the number of hours worked per week. With mineral dusts, and other substances where the half life is in excess of 1000 hours, the calculated adjustment factor is inversely proportional to the increase in average hours worked per week.

As with the Hickey and Reist model, the Roach model is based on ensuring that peak body burden for a special shift roster, such as a twelve hour shift roster, is equal to the peak body burden for the normal eight hour shift roster.

To do this it is necessary to determine at what time in the roster the peak body burden occurs. This is at the end of the shift before which there is least cumulative non exposure time from the start of the work cycle. For a normal five-day work-week cycle this is at the end of the Friday shift. For special work cycles this will normally be at the end of the shift prior to the longest break but this is not always the case, particularly if there are a number of extended breaks of similar length in the cycle.

To determine the shift after which the peak body burden occurs in a special work cycle the cumulative time from the end of each shift to the start of previous shifts is calculated considering each shift as the start of the work cycle. When this value is a minimum the end of the shift in that cycle will be the time in the work cycle where body burden is at its peak because there has been minimal time for decay.

Exposure Standard Adjustment in Australia

In 1996 the Exposure Standards Expert Working group recommended a preferred model for the adjustment of 8-hour time-weighted-average exposure standards for altered workshifts (Exposure Standards Expert Working Group, 1996).

This document highlighted the duty of care required by an employer to consider whether to reduce exposure standards by a suitable factor. This was considered part of the process of assessment and control of hazardous substances in the workplace as required by the *Model Regulations for the Control of Workplace Hazardous Substances* (Worksafe Australia 1994).

The amendment indicated that there were a number of models for adjusting exposure standards for altered work shifts. The selection of an exposure standard adjustment model depended on the information available and the expertise of personnel applying the model as adjustment of exposure standards may be complex. In addition there was no scientific consensus on a universal adjustment regime. In this document the Exposure Standards Expert Working Group recommended the Brief and Scala model be used for calculating adjustments to the exposure standards. The reasons for this were that the model was simple to use, took into account both increased hours of exposure and decreased exposure free time, was more conservative than the OSHA model or the pharmacokinetic model of Hickey and Reist, and it was suitable for use with the Australian exposure standards of the National Occupational Health and Safety Commission. The Expert Working Group did not however exclude the use of the pharmacokinetic model of Hickey and Reist.

Table 2
Summary of Adjustment Factors

Model	Adjustment Factor	
	12 hour shift regime - 14 shifts worked - 4 week cycle	12 hour shift regime 4 on 4 off - 15 week cycle
Adsorbed dose adjustment	0.66	0.66
Brief and Scala	0.5	0.5
OSHA	0.95	0.83
Hickey and Reist	0.91	0.88
Roach	0.93	0.88
Ratio of average hours worked per week in normal schedule to hours worked per week in special schedule	0.95	0.89

DISCUSSION

The absorbed dose adjustment model does not allow for possible decreased recovery time nor does it take into account pharmacokinetics, chemical absorption and excretion. As pharmacokinetics is of paramount importance for chemical toxicity, particularly for cumulative toxins with long half lives, it is considered that this model, though conservative, is not suitable for use with mineral dusts.

The Brief & Scala model is used for adjustment of exposure standards for systemic toxins and is thus not suitable for coal mine dusts. It also does not account for pharmacokinetics and is thus not suitable for use with mineral dusts.

The OSHA model considers specific types of health risk and though it does not consider chemical absorption and excretion rates the result for coal mine dusts is similar to that for the more complex pharmacokinetic models. Due to its relative simplicity this model may be most suitable for use with coal mine dusts. Worksafe Australia does however state that this model is based on use with US exposure standards (Exposure Standards Expert Working Group, 1996). The coal dust and quartz exposure standards in use in Australia do differ from those in the US therefore this model should not be adopted for these mineral dusts.

The pharmacokinetic models, by their nature, account for absorption and excretion. The models simplify these processes by assuming the body is a single compartment where substances are excreted, exhaled, detoxified or otherwise eliminated at a rate proportional to their concentration in the body or the lungs. The body is viewed as a single well mixed compartment of fixed volume with one input and one output. Mathematically this simplifies to first order exponential kinetics with regard to the rate of decay of substances from the body. Elimination of solvents for example actually follows a two compartmental elimination profile. Particles actually follow a three compartmental model:

- rapid clearance from the trachea and nose (10 minutes)
- bronchi elimination (20-30 minutes); and

- parenchymal (lung lining) clearance (greater than 100 minutes).

Particles accumulate in the lung at a rate proportional to the atmospheric concentration. (Guerrini, Flippich and Bourne, 1996). The most significant clearance mechanism with regard to mineral dusts and their health consequences is the parenchymal clearance from the extremities of the lung thus it is this compartment which is considered by the single compartment pharmacokinetic models.

The pharmacokinetic models are based on the premise that limiting body burden will minimise the consequential adverse health effects caused by accumulated substances. This is a somewhat tenuous premise. Adherence to exposure standards adjusted for special shift cycles in accordance with pharmacokinetic models will ensure that the peak lifetime body burden will be no more than would be the case in a normal shift schedule. However it is conceivable that adverse effects could arise from the somewhat different manner in which the body burden has fluctuated in reaching the peak lifetime body burden.

Therefore the pharmacokinetic models do make simplifying assumptions:

- that the body is a single compartment and that processing of contaminants in the body is in accordance with exponential accumulation and decay;
- that clearance is in accordance with the biological half life of chemicals and that this half life does not change with differing exposure patterns.

However the pharmacokinetic models do account for absorption and excretion and use peak body burden, as opposed to average or residual body burden, as the criterion for equating exposure. The use of residual or average body burden would result in a more liberal adjustment of the exposure standard and may not prevent high peaks at time during a special cycle.

Overall pharmacokinetic models are generally considered the most rigorous in terms of a true reflection of health significance and the most accurate when estimating exposure standard adjustment factors.

The Hickey & Reist and Stan Roach pharmacokinetic models give similar adjustment factors for the two 12-hour shift regimes studied in this paper (see Table 2) and this adjustment is approximately proportional to the increased hours worked over the special work cycle. This is due to the long half lives of mineral dusts. The strict mathematical application of the pharmacokinetic models is complex and time consuming and does not result in adjustment factors significantly different from calculating a factor proportional to the overall increase in average hours worked per week for the special cycle.

CONCLUSION

The way in which disease progresses in the human body is dependent on many factors. One such factor may be the pattern of exposure to the contaminant causing the disease. The latency period for the occurrence of illnesses from mineral dust exposure is a considerable length of time. Exposing workers to mineral dust for longer cumulative periods than the normal eight hour shift may shorten the latency period for disease development. Not all people cope with exposure to dust in exactly the same manner. An exposure period to mineral dust for one person may cause no ill health and yet this same exposure may place another person in a situation where serious long term health effects are suffered. Workers are individuals with individual reactions to hazardous substances.

The exposure standards are based on a level at which the majority of workers would be expected to remain free from currently known adverse health effects. Any adjustment to the exposure standards will of course be subject to the same limitations and could involve other adverse consequences due to pattern of exposure.

The adjustment of exposure standards should be done using the most rigorous techniques available. The pharmacokinetic models, though complex, offer techniques that take into account health risk and absorption and excretion of substances in the body. When applied to substances with long half lives the resulting adjustment factor is approximately proportional to the ratio of weekly exposure in a normal eight-hour shift five-day work cycle to average weekly exposure in a special work cycle. Therefore the models reduce to a very simple calculation for use with mineral dusts such as coal and quartz.

For example for a roster of four 12-hr shifts on, four days off, that repeats 14 times in a 15 week long cycle the average weekly exposure is 44.8 hours. Therefore the exposure standard adjustment ratio is 0.89.

For a roster of 14 12-hr shifts that repeats every 4 weeks the average weekly exposure is 42 hours. Therefore the exposure standard adjustment ratio is 0.95.

The adjusted exposure standards for coal and quartz are as per Table 3.

Table 3
Adjusted exposure standards for coal and quartz

Mineral dust	Current 8-hr TWA Exposure Standard	14 shift 4 week cycle		4 on 4 off 15 week cycle	
		Adjustment Factor	Adjusted 12-hr TWA Exposure Standard	Adjustment Factor	Adjusted 12-hr TWA Exposure Standard
Coal	3 mg/m^3	0.95	2.85 mg/m^3	0.89	2.67 mg/m^3
Quartz	0.2 mg/m^3	0.95	0.19 mg/m^3	0.89	0.18 mg/m^3

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