Management of Occupational Exposure Limits: A Guide for Mine Ventilation Engineers

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Abstract. Many underground mines do not have a qualified or dedicated occupational (industrial) hygienist on site, or even available as a resource. Many mine ventilation engineers do not even consider occupational exposure monitoring to be relevant to their role as an engineer. In many cases where occupational exposure monitoring is conducted, the mine ventilation engineer is not informed about the results of the monitoring, or if he is, cannot interpret correctly what these results mean. This bunker mentality separating occupational hygiene and ventilation engineering reduces the range of tools available to the ventilation engineer to actively adjust or tune the ventilation system to keep the underground environment healthy, or as healthy as it could otherwise be. This paper sets out the principles and practices that the mine ventilation engineer needs to know to be able to understand how to interpret occupational hygiene monitoring results, and the implications for the mine primary and secondary ventilation systems.

Keywords: Occupational · Industrial · Hygiene · Monitoring
Underground · Ventilation

1 Introduction

In most countries, occupational (or industrial) hygiene is managed by professional hygienists—quite a different field of specialty to engineers; mine ventilation engineers have only been peripherally involved if at all. The exception is probably South Africa where the role of ventilation engineers now tends to encompass at least basic occupational hygiene management. There are arguments for and against combining the roles of hygienist and engineer, but the dual-role system has not been adopted elsewhere to date. Therefore in most of the world, ventilation engineers and hygienists need to do their separate jobs well and then share their information to get a high-quality result for the workforce. For example, an external (consulting) hygienist may find that a particular group of underground workers has high respirable crystalline silica dust doses, but it is probably the ventilation engineer who is best able to identify where this dust is coming from and assess the range of changes available, taking into account their

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engineering, operational and cost implications, to either eliminate the dust or dilute it, in accordance with the hierarchy of controls. This paper therefore approaches the topic from the perspective of what a ventilation engineer needs to know to support achievement of the overall occupational hygiene outcomes at their mine.

2 Reasons for Managing Exposures to Atmospheric Contaminants

There are important ethical and moral reasons to monitor and manage the doses of airborne (and other) environmental contaminants that workers are being exposed to such as toxic gases, flammable gases, toxic dusts, explosive dusts, diesel particulate matter (DPM), noise, radiation, heat stress and other human environmental hazards.

In addition, there are also legal regulations with criminal penalties and the more general "Duty of Care" as well as "ALARA/P" (as low as reasonably achievable/practicable) is also frequently a legal requirement. Monitoring *changes* in exposures over time is also important as one of the principles of proving ALARA is to demonstrate that doses are reducing over time, i.e. the operation is achieving "continuous improvement" and this requires an ongoing, rather than one-off, monitoring program.

There are also sound economic reasons for monitoring occupational exposures. Firstly, in some jurisdictions, it may be allowable to reduce airflows in part or all of the mine (saving capital and operating costs) below some otherwise prescriptive value (such as 0.06 m^3/s per kW diesel) providing a monitoring program demonstrates (i.e. proves) contaminant doses are safe. Secondly, the legally allowed dose limits of many contaminants have been lowered in the past and will further reduce with time as more medical research is completed, and in some cases, legal claims (e.g. for lung disease), including large class action cases have been initiated many years after exposure, so that monitoring doses and keeping sound records is good business.

3 The Different Roles of Key Professional Groups

The measurement and management of environmental exposures to hazards is the practice of occupational (or industrial) hygiene. The clinical detection and treatment of occupational disease is the practice of occupational medicine (physicians). The prevention of occupational disease is achieved by occupational hygiene monitoring programs (conducted by hygienists) and health surveillance programs (conducted by physicians).

The ventilation department in an underground mine should have a critically important role to play in occupational hygiene management. However, the ventilation department must also measure and manage other hazards (or assist with this process) that are not considered to be within the role of the occupational hygiene such as explosive gases and dusts. The safety department may have input into these areas and also the maintenance department (e.g. in terms of measuring tailpipe (raw) engine gas and diesel particulate emissions).

An important issue is that the ventilation officers should be underground daily assessing and managing the ventilation circuits, and are therefore often the most informed personnel on site about underground airborne environmental conditions, the sources of the contaminants and the reasons for the concentrations, as occupational hygienists or physicians will be underground much less frequently.

4 Types of Monitoring Programs

It is important to understand and "risk assess" the full range of potential sources of environmental contaminants in the workplace, both those produced as part of the normal work process and those produced in "upset" conditions such as mine fires or the failure of seals into old areas of the mine.

Various types of monitoring programs will be used to manage these risks. Examples include:

- Measuring raw or undiluted tailpipe emissions of gas or DPM from diesel vehicles on a regular basis. Vehicles with high values are then monitored more regularly, or sent off for engine or emissions systems' servicing, rebuild or replacement.
- Measuring "general body" gas or dust concentrations (or temperature, radiation, etc.) where persons are working. This includes both:
  - Spot checks at single points in time
  - Time-averaged "fixed location" measurements or area sampling
  - Real-time continuous "fixed location" measurements or area sampling.

- Measuring doses of dust or DPM for individuals and groups over full working shifts using personal samplers
- Re-entry (clearance) gas checks after blasting
- Procedures to measure and manage toxic or explosive gases including behind seals or in unventilated or worked-out areas
- Confined space procedures
- Health surveillance programs utilising lung function tests, chest x-rays or audiometry (hearing loss) tests, etc.

Note that the overall dose of a contaminant to an individual may not be solely via breathing, and in such cases cannot be controlled purely by managing the atmosphere and the ventilation circuits. Such examples would be:

- Blood lead levels, which are also affected by biting fingernails, eating with unwashed hands, smoking, etc.
- Radiation doses which are also affected by direct gamma ray irradiation
- Heat stress which is affected by a combination of many factors.

For these reasons, every mine should have an approved overall Occupational Hygiene Management Plan for the operation.

It is also important to note that allowable *occupational* doses are usually much higher than allowable doses for the *general public*. There are many reasons for this, but one is that workers are only exposed to occupational doses for an average of about 40 h per week or about 2000 h per year, whereas the public, if exposed by virtue of where they live, can be subject to 365 × 24 or 8760 h exposure per year. Also the general public includes babies, the elderly and the sick—all of whom often have lower tolerance than healthy workers.

Regarding the legal standing of exposure limits (ES) for respirable hazards, the following points should be noted:

- The laws relate to *personal* measurements, i.e. not "static" or fixed location concentration.
- In most cases the personal measurement is the *dose* over some period of time.
- The sampling location should always be in the "breathing zone" of the person, the exact definition depends on the jurisdiction.
- The law is generally silent on the statistical treatment of exposure measurements. The law deals in absolutes which implies that even a single over-exposure to a single worker at a single day would be a breech.[1] However, this would mean that virtually all workplaces would be non-compliant. Therefore some form of statistical analysis appears both valid and necessary, even if there is no legal provision for same.
- Similarly, the law is couched in terms of exposures of individual persons not exposures of similarly exposed sample groups of workers.

5 Making the Information Available

Reputable mining companies will often make their key safety and health policies public (e.g. [4]) and often publish their overall performance, and future targets, to the public. At the very least, measured occupational doses should be advised to the individuals concerned after every set of measurements, and aggregated data for groups of workers provided to key stakeholders such as that group of workers, the individuals' line management and the ventilation engineer.

6 Limits for Exposures, Sample Size and Sampling Strategy

There are in practice many types of exposure standards (ES), often called "threshold limit values" or TLVs, a term owned and copyrighted by the American Conference of Government Industrial Hygienists. These include time weighted average

[1] OSHA in 1978: "OSHA recognizes that there will be day-to-day variability in airborne lead exposure experienced by a single employee. The permissible exposure limit is a maximum allowable value which is not to be exceeded: hence exposure must be controlled to an average value well below the permissible exposure limit in order to remain in compliance" [5].

(TLV-TWA[2,3]), short-term exposure limits (TLV-STEL[4]) and Ceiling[5] (or Peak) limits (TLV-C). There are also "Immediate danger to life and health" (IDLH) limits which relate to emergency conditions rather than normal operating conditions. Ceiling limits are, in effect, instantaneous airborne concentration limits rather than time-weighted doses.

Note that some legislation mandates "maximum allowable concentrations" (MACs) or similar, and these are ceiling limit concentrations not time-weighted dose limits. The ventilation engineer needs to be familiar with both concentration and dose limits.

The limits for gases are usually volume by volume concentrations (e.g. ppm), particulates are mass by volume concentrations (e.g. mg/m^3), fibres such as asbestos are fibres per milliliter of air and biological agents such as Legionella (found sometimes in underground cooling towers) are colony-forming units per litre (CFU/litre of water).

It should also be remembered that some concentration limits (especially O_2, CO_2 and CO) will be affected by altitude. Specialist advise should be sought in such cases.

The choice of the numerical limit will depend on a variety of factors, but good practice would be to use the lower (i.e. more conservative) of either the value stipulated by law in the local jurisdiction, or some global value chosen by the mining company based on first-world standards. In many cases, the mine may voluntarily choose an Internal Limit (IL) that is lower than the legal requirement. This is particularly the case

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[2] An ACGIH term: "The concentration for a conventional 8-h workday and a 40-h workweek, to which it is believed that nearly all workers may be repeatedly exposed, day after day, for a working lifetime without adverse effect. Although calculating the average concentration for a workweek, rather than a workday, may be appropriate in some instances, ACGIH does not offer guidance regarding such exposures".

[3] And also "Occupational exposure limits" (OELs), "Permissible exposure limits" (PELs), "Recommended exposure limits" (RELs) and "Workplace exposure limits" (WELs). There can be subtle differences in the definitions of these terms and the ventilation engineer should be certain which applies to his mine.

[4] An ACGIH term: "A 15-min TWA exposure that should not be exceeded at any time during a workday, even if the 8-h TWA is within the TLV–TWA. The TLV–STEL is the concentration to which it is believed that workers can be exposed continuously for a short period of time without suffering from (1) irritation, (2) chronic or irreversible tissue damage, (3) dose-rate-dependent toxic effects, or (4) narcosis of sufficient degree to increase the likelihood of accidental injury, impaired self-rescue, or materially reduced work efficiency. The TLV–STEL will not necessarily protect against these effects if the daily TLV–TWA is exceeded. The TLV–STEL usually supplements the TLV–TWA where there are recognized acute effects from a substance whose toxic effects are primarily of a chronic nature; however, the TLV–STEL may be a separate, independent exposure guideline. Exposures above the TLV–TWA up to the TLV–STEL should be less than 15 min, should occur less than four times per day, and there should be at least 60 min between successive exposures in this range. An averaging period other than 15 min may be recommended when this is warranted by observed biological effects".

[5] An ACGIH term: "The concentration that should not be exceeded during any part of the working exposure. If instantaneous measurements are not available, sampling should be conducted for the minimum period of time sufficient to detect exposures at or above the ceiling value. ACGIH believes that TLVs based on physical irritation should be considered no less binding than those based on physical impairment. There is increasing evidence that physical irritation may initiate, promote, or accelerate adverse health effects through interaction with other chemical or biological agents or through other mechanisms".

if achieving the IL is relatively easy (and is therefore targeting a lower limit is entirely in accordance with the ALARA principle).

It is also important to note that a legal limit should never be viewed as a clear demarcation line between a “safe” and an “unsafe” level; hence the need to apply ALARA. As an example, if the TWA for ammonia is 25 ppm, this does not mean that 25 ppm is “safe” and 26 ppm is “unsafe”.

Almost all ESs are based on a traditional work roster of 5 $\times$ 8 h shifts per week. Where workers are on other rosters (e.g. 12-h shifts) then an adjustment must be made to these 8-h values. The recommended guideline in Australian mining is from WA Resources Safety [14], mainly because it specifically addresses the “fly-in, fly-out” non-standard rosters commonly used in the Australian mining industry. However, other guidelines are also available [2, 6]. Where synergistic effects may occur due to exposure to two or more contaminants, ESs may need further adjustment using an approved procedure as ESs only apply for exposure to one substance at a time.

Any contaminant listed in a document such as the ACGIH TLVs [1], or Safe Work Australia [12], requires monitoring. However, non-toxic but otherwise hazardous substances may also require monitoring. These include explosive gases such as methane, simple asphyxiants such as nitrogen or non-toxic dusts often called “Particles not otherwise classified” (PNOC[6]). In terms of knowing what contaminants to monitor, a thorough, systematic and documented analysis of the environment and each workplace and work activity is needed, typically a *qualitative* occupational hygiene survey followed up by a more targeted *quantitative* occupational hygiene survey. For example, if a qualitative survey finds that diesel equipment is in use, then diesel exhaust gases and DPM will be present and probably need to be measured in the quantitative survey. If some of the minerals being mined are sulphides, then there is the potential (depending on the exact mineralogy) for SO_2, H_2S, sulphide dust explosions or spontaneous combustion hazards to be present. Silica is often present in mines and can result in crystalline silica dust of respirable size entering the air. Metals in the minerals such as lead or mercury are also toxic with one of the pathways into the body being via inhalation. Certain strata may result in CH_4, H_2, CO_2 or other gases being released. Contaminants can also be introduced via chemicals in use, or other parts of the mining cycle such as cement used in ground support. Where exploration drilling notes “bubbles of gas” being produced in the drilling fluid, samples of such gas should be collected in suitable bags and analysed in a gas chromatograph.

Any monitoring program and the choice of exposure or dose levels should be tailored to and prioritised by the toxicity or hazard of the contaminant and the number of persons exposed. In addition, the internal response of the organisation should usually be progressive, i.e. using “action levels” or a Trigger Action Response Plan (TARP) so that detection of low levels of a contaminant triggers an initial response involving more frequent monitoring, whilst detecting higher levels triggers more profound and rigorous responses. Management interventions should comply with the Hierarchy of Controls.

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[6] Particles not otherwise classified (PNOC) are also referred to by alternate authorities as Particles not otherwise specified (PNOS) or Particles not otherwise regulated (PNOR).

A typical requirement would be for an ES management plan to be implemented where particulates exceed 1/10th of the ES or gases exceed ½ the ES [10].

Where the technology exists, some occupational doses can be continuously measured *individually* for each person. An example is gamma radiation. However, in most cases of airborne respirable contaminants, continuous personal measurement is impractical and the statistically appropriate way of managing occupational exposures is to divide the workforce into groups of workers who do the same or very similar jobs and who will all therefore be exposed to the same dose of airborne contaminants. Such groups are called “Similarly (or Homogenous) Exposed Groups” (SEGs or HEGs).

A statistically valid sample of workers from each SEG is monitored regularly. To avoid any bias, this sample is chosen randomly for each new sampling program so that some individuals are not always being monitored and others never being monitored.

The division of the workforce (including contractors) into SEGs and the choice of sample size within each SEG for routine measurement, the measurement intervals, techniques and equipment must all comply with a recognised standard and good practice. In general, the sample size should be such that at least one worker from each SEG will be within the top 10% of exposures of that SEG population to a 95% confidence limit. Note that for small SEG sizes, this may mean sampling all or almost all persons in the SEG each sampling interval. Guidance on sample sizes can be found in many documents [7–11, 13]. It is certainly not good enough to merely do what is expedient.

The South African Codebook [11] describes a way of separating the workforce into HEGs in which a HEG is only correctly populated if both the average and 90th percentile of the HEG fall in the same classification band. If this is not the case, then the workers in the HEG must be sub-divided or reclassified. However, it is difficult to see any justification for this practice and to this author’s knowledge it is not applied elsewhere.

The actual sampling device and sampling procedures must also conform to an accepted standard such as AS2985-2009 [3]. In the case of respirable dust, the samplers ensure only the respirable fraction of the dust is sampled.[7] The sampling period should

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[7] Quoting from AS 2985-2009: “Occupational hygiene practice commonly differentiates between two size fractions of airborne dust, namely respirable and inhalable dust. Where particles may have toxic effects if absorbed in the nasopharyngeal (nose and throat) region or may have toxic effects if ingested after deposition in this region, it is appropriate to measure the mass concentration of inhalable particles in the atmosphere. It may also be apt to measure this size fraction for particles that exhibit no specific toxic effects, namely ‘particulates/dusts not otherwise classified.’ … Respirable particles can be measured when the nature of these particles is such that they exhibit toxic effects primarily when deposited in the alveolar region (deepest reserve) of the lungs. This usually applies to toxic insoluble particles that accumulate in the lungs such as crystalline silica, coal dust and cadmium oxide fume…

> Respirable dust: The proportion of airborne particulate matter that penetrates to the unciliated airways when inhaled. This fraction is further described in ISO 7708 as the percentage of inhalable matter collected by a device conforming to a sampling efficiency curve that passes through the points shown in Table 1. Alternatively, it can be described by a cumulative log-normal distribution with a median EAD of 4.25 μm and a geometric standard deviation of 1.5 μm.

be "as long as possible", with a minimum of 4 working hours, but preferably a full working shift. *Sampling strategies must never be chosen to deliberately under-report the doses*.

In theory, where workers are required to wear respiratory protective equipment (RPE) during parts of their work activity, it is acceptable to calculate their respirable doses taking into account the reduction achieved by the RPE. For example, if a worker is wearing RPE with a minimum protection factor of 10, then the respirable dust (say) measured by the sampling device (which does not have RPE on its air inlet, unlike the worker) for that period of time can be reduced by 10. However, good practice is to *not* do this for many reasons. Firstly it requires very detailed observation of the worker during the shift (assuming RPE must not be worn all shift by the worker). Secondly it requires the dust doses to be measured separately when RPE is being worn versus when it is not. Thirdly, it assumes the RPE is worn "as required" at other times (when sampling is not being undertaken and therefore the worker is not being observed). And fourthly, it assumes the RPE is achieving its rated protection factor (which may not be the case, e.g. if there is any facial hair or even minor stubble).

Good practice is generally for a medical surveillance program to be adopted for all workers in any SEG that exceeds 50% of the allowable ES. This adds extra costs and complexity to having workers subject to more than 50% of the ES allowable doses and would be an incentive to keep SEGs below 50% of the ES.

7 Statistical Analysis and Interpretation of the Sampling Data

A correct and auditable statistical analysis of the sample data is very important. Some important points to understand in interpreting the data are:

- Most occupational exposure doses follow a log-normal distribution[8] (Fig. 1). Note the arithmetic and geometric means are different values as is the mode (most common value). The geometric mean is usually taken to be the best indicator of the average of the sample, especially small samples. In a true log-normal distribution, the geometric mean and median are identical. However, in some cases the geometric mean (median) is not the best estimator of the average. In such cases it is usual to use either the maximum likelihood estimator (MLE) or the minimum variance unbiased estimator (MVUE) to assess the SEG position.[9] Suitably competent persons should make this statistical assessment in accordance with recognised guidelines.

[8] Where exposures are *very tightly controlled*, the types of factors that lead to a log-normal distribution may not be present, and the distribution may be "normal". This should be checked.

[9] Where the "test" is to ensure the sample population is *below* an exposure standard, then a "one-tailed" test is sufficient, i.e. the UCL is effectively set at the 95% on its own.

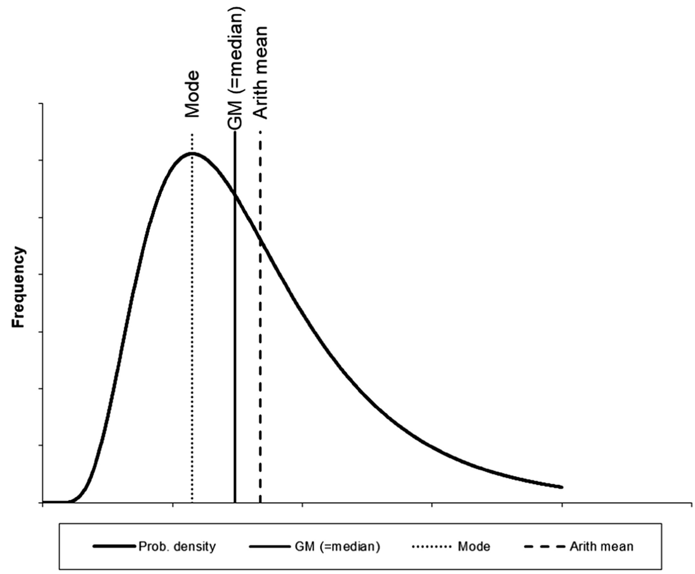

Fig. 1. Log-normal distribution showing the mode, geometric mean (median) and the arithmetic mean

- The true average (or MVUE) for a SEG is unknown and unknowable. Correct statistical treatment means that the true average lies somewhere (unknown) between the Lower and Upper Control Limits (LCL and the UCL). Effectively, since 95% of the population is expected to lie between the LCL and the UCL, this means 2.5% of the population of the SEG is expected to be above the UCL and hence above the ES. To be suitably "confident" (in the statistical sense) that the average is *lower* than the ES, the UCL for the sample must be lower than the ES (Fig. 2). In most cases, the average of the sample must be very much less than the UCL to comply, and in fact it is possible that almost all the individual measurements can comply but the sample as a whole still "fail".
- Conversely, if the LCL is above the ES, then the SEG has certainly "failed" (Fig. 4).
- Where the ES lies between the LCL and the UCL, then the SEG "may" have passed or "may" have failed (Fig. 3). This should be treated as a "fail" or "exceedance".
- Therefore if legislation states that exposures "must not be above" the limit, then regulators cannot (technically) require exposures to be "below" the limit.[10] Hence whilst Fig. 3 may have some or even most measurements above the ES, because the LCL is still lower than the ES, this sample still "is not above the exposure limit"

[10] The Safe Work Australia requirement is "no employee is exposed at levels *above* the appropriate exposure standards" (this author's italics). Exposure *at* the exposure limit is acceptable.

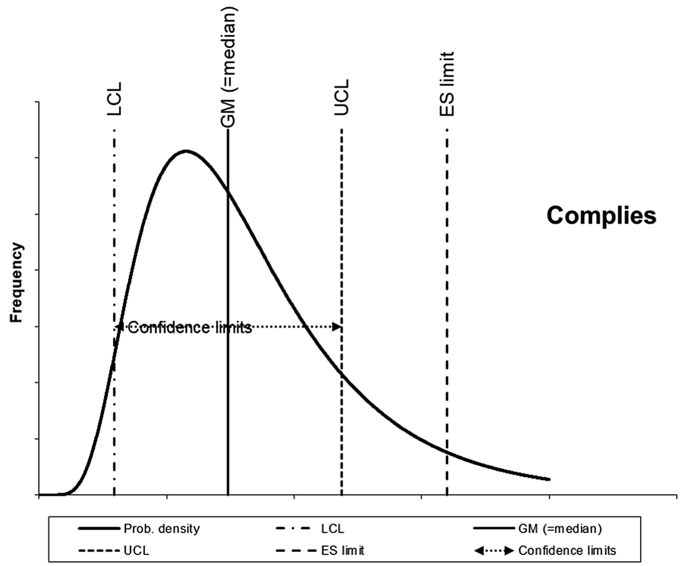

Fig. 2. This SEG does comply with the exposure standard (ES)

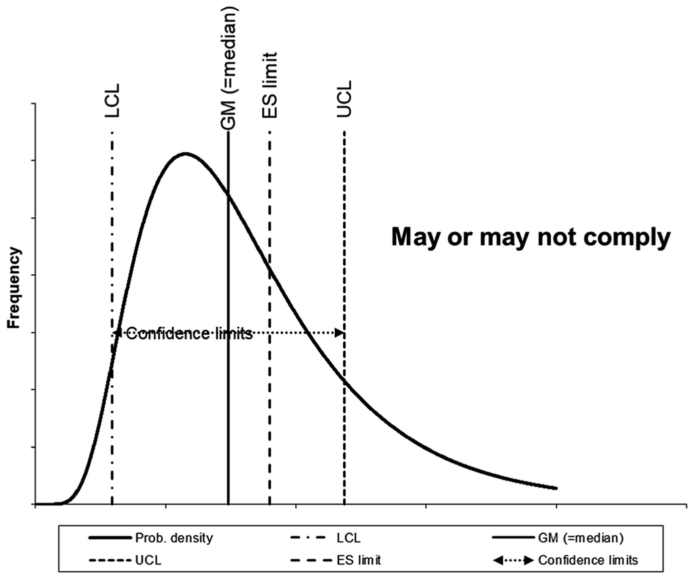

Fig. 3. This SEG may or may not comply with the exposure standard

(from a statistical standpoint). However, it is important to emphasise that most reputable employers will seek to manage exposures so that they are below the ES, i.e. the UCL is below the ES (Fig. 2) and not merely that the LCL is not above the ES (Fig. 4).

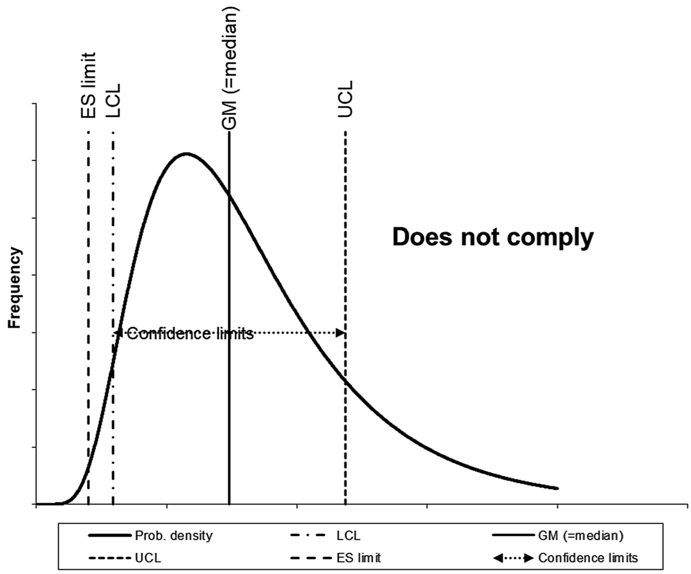

Fig. 4. This SEG does not comply with the exposure standard

- In effect, this means the number of "exceedances" (for any contaminant) is not the number of persons measured that failed, but the total population of each SEG that failed. It further means that only "2 or 3 more" failed results in a testing program can push the entire SEG population into the "fail" (exceedances) criteria.
- The sampling interval will depend on how close the measured values are to the ES. Note that where exposures are either very low or much above the ES, then sampling interval is extended (conducted less frequently). For high exposures, this reflects the fact that RPE (respiratory protection equipment) will be required and in use. For very high exposures, sampling is required to audit the protection being provided by the RPE. For example, if the UCL for a SEG is under 25% of the ES, then infrequent sampling may be reasonable. If the UCL is more than 100% of the SEG, then again, only infrequent sampling is needed assuming no efforts are made to reduce the dose exposures. Where the UCL is between 25 and 50% then more frequent monitoring may be required to avoid triggering a medical surveillance program. Where the UCL is between 50 and 100%, then more frequent monitoring may be required to take action to avoid exceeding the ES. SEGs with UCLs falling between 25 and 100% of the ES are the most critical in terms of monitoring.

Note also that there will not be a linear relationship between the average concentrations in the air and the number of exceedances.

8 Case Example

A lead-zinc mine conducted sampling for blood lead levels and obtained the values shown in Fig. 5. The UCL for the SEG for the "UG Crusher operators" exceeds the ES, and therefore *all* workers in this SEG are considered to exceed the ES (i.e. are "exceedances") even though testing of this group may show only a few actually do. For example, if there were 20 "UG Crusher operators" in the mine and 10 were sampled from this SEG and 8 of those 10 were below the ES ("passed"), but the UCL was above the ES, then all *20 UG Crusher operators should be treated as "fails" (exceedances) even though only 2 actually "failed"*.

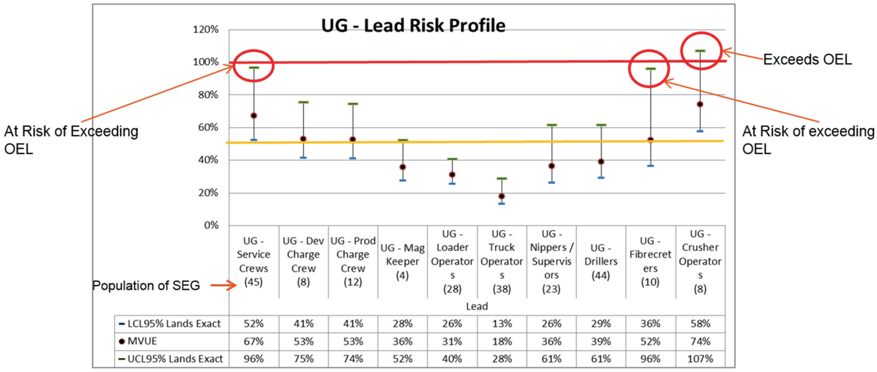

Fig. 5. The blood lead levels for a number of SEGs at one underground mine

A similar situation exists in Fig. 6 with respect to diesel particulate matter results. All but one of the SEGs had average values below the ES, but the UCL for most SEGs is above the ES, so all workers in that SEG (whether sampled or not, and whether they individually passed or not) are treated as "fails" (exceedances).

As discussed earlier, not only should exceedances be "nil", but the *trend* in exposures should show a decrease with time. Therefore examining the trend of exposures for each SEG is important as it will allow the ventilation engineer to see which ones are trending either towards non-compliance or compliance.

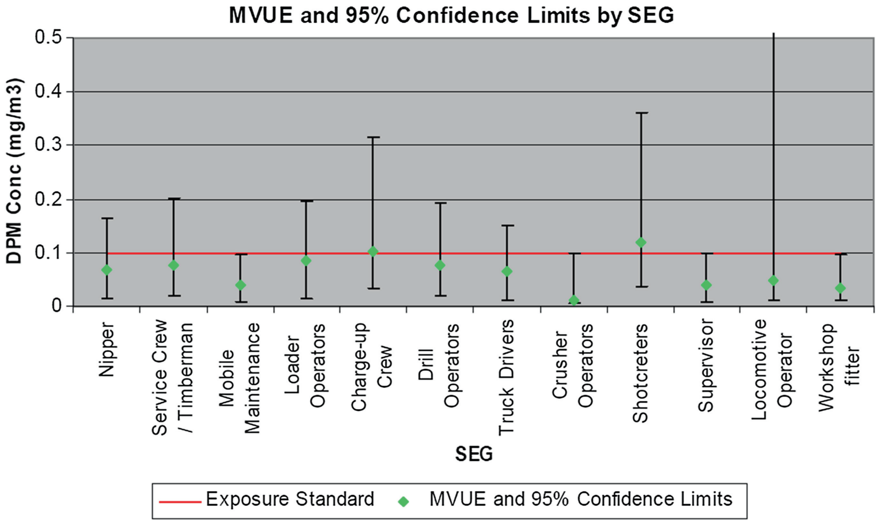

Fig. 6. DPM hygiene monitoring results

9 Conclusions

Occupational hygiene monitoring is rarely the responsibility of the mine ventilation engineer and ventilation engineers, if ever, have sufficient training to taken on the role of a professional hygienist. However, it is essential that occupational hygiene monitoring is being completed on all mine sites according to an approved Management plan and an informed ventilation engineer is in a better position to help ensure this is being done and is being done properly. It is equally important that the data obtained under this hygiene management plan is then shared with a ventilation engineer who can understand what it means, and its limitations, and who should then be charged with reviewing the range of controls for particular groups of workers, and the performance of the ventilation system in certain locations of the mine or at certain periods of time or activity. When accompanied by other measurements, including routine hand-held sampling and "fixed location" sampling for dusts, DPM and gases, the interpretation of the data provides a powerful way to not only ensure compliance with legislation and good practice, but also to assess the effectiveness of various controls, including the primary and secondary ventilation systems themselves.

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