Commentary

Diesel Particulates—Recent Progress on an Old Issue

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Over the past 115 years the invention of a compression ignition engine by Rudolph Diesel in the 1890s has contributed significantly to the productivity of many nations, owing to the widespread use of larger diesel powered equipment in most industrial activities. The down-side in terms of occupational health has been the exposure of a large number of workers to the complex mixture of toxic, gaseous, adsorbed organics and particulate components found in the raw exhaust emissions.

Although the adverse health effects of the gaseous fraction of diesel emissions have been known for sometime, only in the last two decades has research indicated that the particulate component of the diesel exhaust has the potential to induce various health effects. In addition, it is associated with non-health aspects such as malodour, visual and nuisance pollution.

Diesel exhaust emissions were investigated >20 years by the BOHS Hygiene Standards Committee (BOHS, 1981). The Committee’s terms of reference were;

(i) Which gaseous constituents in diesel fume are of hygienic significance?
(ii) How should these contaminants be assessed?
(iii) How these arrangements may be interpreted in terms of human response?
(iv) Is there a simplified air sampling and analytical procedure which could be devised and which would provide adequate information to enable subjective response to be predicted?
(v) What is the hygienic importance of the particulate content of diesel fume and how this may be assessed?

The Committee concluded that the components of diesel emissions were a complex mixture and hence no ready method of monitoring was available. The then available information on health effects was scant and inconclusive. However, it was observed that diesel fumes became objectionable and intolerable even before the reach of concentrations at which known toxic effects might be expected to occur. It recognized that diesel soot was a poor source of polycyclic aromatic hydrocarbons and there was no evidence from epidemiological studies that exposure to diesel exhaust caused lung cancer, but expressed the need for constant vigilance as new assessment techniques became available.

We have now reached a stage where regulatory authorities are promulgating legislation to control exposure to diesel particulates, and it is useful to look at a few milestones that have occurred since the original BOHS report.

HEALTH EFFECTS AND RISK

The next defining moment on the health issue possibly occurred when NIOSH (1988) published Criteria Bulletin No. 50 which proposed a potential link between occupational exposure to diesel exhaust and lung cancer. The NIOSH finding was based on the consistency of toxicological studies in rats and mice and limited epidemiological evidence, mainly from the railroad workers.

The IARC evaluation 2A is based on limited evidence in humans and sufficient evidence of carcinogenic risk in animal studies (IARC, 1989).

The Health Effects Institute (HEI, 1995) undertook a review of the toxicological studies including acute and chronic effects. It also included the 30 epidemiological studies of workers exposed to
diesel emissions in occupational settings for the period 1950–1980. HEI concluded that the epidemiological data indicated weak associations between exposure to diesel exhaust and lung cancer with a relative risk of 1.2–1.5. They issued a note of caution indicating that all the studies had a lack of definitive exposure data and had an inability to determine the influence of confounding factors, such as tobacco smoking.

Mines Safety and Health Administration (MSHA, 2001b) reviewed 47 epidemiological studies and determined that in 41 studies there was some degree of association between occupational exposure to diesel particulate matter and an excess prevalence of lung cancer. However, some of these studies had limited statistical power either because they included relatively few workers or had an inadequate allowance for latency or follow-up period. MSHA then concluded that exposure at a mean concentration of 0.64 mg m\(^{-3}\) DP for a period of 45 years would result in a relative risk of 2.0 for lung cancer.

The United States Environmental Protection Agency (US EPA) conducted a health assessment for diesel engine exhaust (US EPA, 2002). They concluded that acute effects with respect to health, such as eye, throat and bronchial irritation, light-headedness, nausea, cough and phlegm were evident. With respect to chronic non-cancer respiratory effects they suggested, from animal studies, the potential for chronic respiratory disease in humans. The EPA also concluded that lung cancer was evident in occupationally exposed groups, but could not define sufficient dose–response data to produce a quantitative risk assessment.

Based on their interpretation of the toxicological and epidemiological data, regulatory authorities in USA, Europe and Canada have concluded that sufficient evidence exists to indicate that diesel particulate presents an increased risk of lung cancer, although the absolute quantification of potency remains unclear.

**MONITORING EXPOSURES**

Beginning 1970, diesel soot in some mining areas was monitored by placing respirable dust samples collected on silver membrane filters and measuring the weight loss after heating in a muffle furnace at 400°C for 1 h (Respirable Combustible Dust). Researchers from NIOSH and the US Bureau of Mines investigated the size distribution of aerosols in dieselized and non-dieselized mines and developed a sampler with a cut point of 0.8 μm which effectively separated the diesel particulate fraction from other mine aerosols (Cantrell and Rubow, 1991). A commercial single use cassette incorporating precision sapphire nozzles, an oiled impactor plate and a quartz fibre filter (SKC 225-317) has been developed to meet the sampling requirements specific for the hard rock mining industry; it has also found widespread use in general industry (MSHA, 1991b).

The surrogate analyte for diesel particulate in the sub-micrometre aerosol fraction is found in carbon speciation analysis. This can be conducted using a thermal–optical instrument based on controlled temperature ramping and combustion to separate organic, carbonates and elemental carbon (Birch and Cary, 1996) and is formally recognized as NIOSH Analytical Method 5040 (NIOSH, 2003). A coulometric separation method is used in Germany (Dahman and Bauer, 1997). Provided that certain parameters are kept consistent, there is reasonable agreement between various laboratories and methods of analysis (Birch, 1998).

Almost all of the diesel particulate has been found to be in the sub-micrometre fraction of the respirable aerosol. The sub-micrometre fraction referred to in the early literature consists of diesel particulate (80–85%), mineral matter and other fine aerosols. Diesel particulate consists of a disordered graphic carbon core (elemental carbon) and adsorbed organics. The content of elemental carbon in the sub-micrometre fraction is ~50% of the total carbon content.

**WORKPLACE EXPOSURE STANDARDS**

The development of an exposure standard remains in a state of flux, partly because of the paucity of dose–response risk data, differing approaches to exposure measurement, and different approaches by various industry segments, advisory groups and regulatory authorities.

Only a few international exposure standard values have been adopted and these mainly relate to higher exposed groups, such as those in the underground mining and tunnelling industries. The standards are linked to specific sampling and analytical methods and hence have limitations when applied in other industries.

Over the last 10–15 years there has been a general development of consensus that the sub-micrometre fraction of various carbon species, such as elemental carbon, is the appropriate surrogate measure for diesel particulate exposure.

Research across the Australian mining industry has found that if atmospheric levels of diesel particulate are reduced <0.2 mg m\(^{-3}\) of sub-micrometre diesel particulate (equivalent to 0.16 mg m\(^{-3}\) submicrometre total carbon or ~0.1 mg m\(^{-3}\) of submicrometre elemental carbon), the level of eye and upper respiratory tract irritation is significantly reduced (Pratt et al., 1995; Rogers and Davies, 2001). Based partly on this research a tripartite industry group within the NSW Minerals Council (1999) proposed an industry best practice standard using these values. Adoption of this strategy within some
sectors of the Australian underground coal mining industry has reduced employee irritant effects and increased productivity. However, the issue as to whether this results in a reduced lung cancer outcome remains unresolved, as the current level of lung cancer in the industry is relatively low (SMR 0.82 95% CI 0.73–0.92) (Brown et al., 1997). This finding is consistent with other international studies on coal miners (IARC, 1997).

About the same time, the MSHA proposed a standard of 0.16 mg m$^{-3}$ sub-micrometre total carbon for use in the underground metal and non-metal mines. The final rule allowed an interim value of 0.4 mg m$^{-3}$ with a move to 0.16 mg m$^{-3}$ by 2006 (MSHA, 2001b). In the coal mines no such exposure standard was set; rather control was to be achieved by limiting the quantity of raw exhaust emissions by ventilation and engineering solutions (MSHA, 2001a).

ACGIH earlier proposed and then withdrew a number of draft and intended changes for a diesel particulate TLV. Diesel exhaust is currently listed as a substance under study (ACGIH, 2005).

**OCCUPATIONAL HYGIENE CONTROL SOLUTIONS**

The various options for controlling diesel particulate emissions have been researched and trialled extensively in the mining industries. Reduction in exposure $\sim80\%$ or more are achievable using existing technologies with the most encouraging data coming from new technology engine design. Details of the ongoing developments and application can be found on the various web pages (DEEP, 2005; MSHA, 2005).

The Australian Institute of Occupational Hygienists has produced a guidance booklet for its members indicating the contemporary findings on various control options from fuel quality, exhaust treatment devices, engine design and engine maintenance, ventilation and respiratory protection (Davies and Rogers, 2004).

Based on the information contained in this document and other applied research findings, some Australian industries and mining companies operating in the international arena have implemented diesel exhaust management initiatives which set out specific responsibilities and actions to control diesel particulates by the use of clean fleet, maintenance systems, ventilation and training.

**RAW EXHAUST PARTICULATE MONITORING**

Current investigations indicate that monitoring particulates and gases in the raw diesel exhaust prior to vehicle use provides information on the likelihood of overexposure of the workforce. Traditional methods of monitoring raw exhaust particulates using light scattering instruments are subject to considerable interference. More specific instrumentation has been developed based on direct exhaust measurement of organic and elemental carbon (Davies, 2000) and indirect soot measurements using pressure differential instrumentation (NSW, 2004; J. C. Volkwein, S. Mischler, B. Davies, C. Ellis 2005, submitted for publication). These instruments allow determination of dirty engines prior to use in the work environment and also provide considerable benefit in terms of diagnostic maintenance and optimization of fuel efficiency.

**CONCLUSION**

Most informed professionals would recognize, based on some of the animal and epidemiological studies, that diesel particulate is a potential carcinogen. Many may also have serious concerns as to the degree of potency being assigned to diesel particulates by some regulatory authorities. It is most likely that as many substances the issue may never be completely defined owing to the lack of sufficient exposure data and control of confounders in the studied populations. There is little doubt that this area of the health debate will continue for sometime within the scientific and regulatory community.

There is an emerging trend within the occupational hygiene community to take a pragmatic approach to measure and control exposures of the noxious and malodorous emissions without attempting to define a dose response based exposure standard.

Given the current community and regulatory pressure being placed on the petroleum industry, diesel engine manufacturers, and the end users, it will be interesting to monitor the evolution of the debate over the coming years.

**REFERENCES**


