Barometric hazards within the context of deep-level mining

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Synopsis

This paper considers potential risks to the health of workers in ultra-deep mines, including barotrauma, physiological effects and toxicity of airborne pollutants. Relevant previous research is reviewed, including work by the Chamber of Mines Research Organization and the DeepMine Cooperative Research Programme, and recommendations are offered for prospectively limiting pressure-related health risks.

Introduction

Most research into barometric hazards has focused on extreme pressures, particularly the hypobaric conditions experienced by mountaineers and aviators, and the hyperbaric conditions affecting underwater divers at great depth. Hypobaric conditions can cause adverse health effects from low partial pressure of oxygen, whereas hyperbaric conditions can result in narcosis from inert gases or toxicity of oxygen and carbon dioxide (Popendorf, 1997).

Due to ever-increasing working depths, the South African gold mining industry has periodically examined the potential risks from exposure to changes in barometric pressure, to evaluate possible negative impact on the health and physical work capacity of underground workers (Van der Linde *et al.*, 1986; Williams *et al.*, 1967). Plans to mine at depths as great as 5 000 m have led to more recent investigations into the potential risk of barotrauma during vertical conveyance of people in ultra-deep mines (Franz, 2000-a), and the toxicity of airborne pollutants at increased barometric pressure (Franz, 2000-b).

General considerations

The total increase in barometric pressure while descending from surface to a mining depth of 5 000 m would be approximately 0.55 ATA (Atmosphere Absolute), i.e. a 66% increase in ambient pressure compared with surface. This is equivalent to a depth of 7 m in seawater, not enough to produce decompression sickness, narcosis or toxic effects among recreational divers. This indicates little risk of routine pressure-related effects during descent into an ultra-deep mine and even less risk during ascent, assuming good dental care, healthy sinuses, unobstructed external ear canals and normally functioning Eustachian tubes.

Barotrauma

Barotrauma is a pressure-induced injury occurring when a gas-filled body space not in communication with the environment is prevented from equalizing pressure differences or maintaining a constant volume during changes in ambient pressure. Pain and barotrauma caused by expansion or contaction of gases during transitions between pressure zones are the most direct effects predictable from Boyle's law, which states that at a constant temperature, the volume of a gas is inversely proportional to pressure. Hence, a change in ambient pressure will result in an inverse change in volume, unless the contained gas is able to move between the body space and the environment. Barotrauma can affect the ears (Hamilton-Farell and Bhattacharrya, 2004), the sinuses (Garges, 1985; Neuman *et al.*, 1975), the lungs (Benton *et al.*, 1996) and the gastrointestinal tract (Molenat and Boussuges, 1995). Dental abscesses and cavities also contain gas and may become extremely painful with changes in ambient pressure (Goethe *et al.*, 1989; Rottman, 1981).

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Physiological effect of pressure oscillations

Van der Linde *et al.* (1986) found no potential for daily oscillations in barometric pressure to induce adverse physiological effects among workers in deep-level operations, other than those on the ears, sinuses and teeth referred to above. They estimated that only at a mining depth greater than 6 000m would pressure oscillations be sufficient to cause decompression sickness, and that nitrogen narcosis and oxygen toxicity would only become possible at depths of 16 000 m and 22 000 m respectively. In fact, their results indicated that at an ambient pressure of 117 kPa (depth of 1 970 m), near-maximal physical work rates were better tolerated with respect to body temperature, partial pressure and saturation of oxygen in venous blood, as well as serum glucose and lactate levels. This was attributed to the higher partial pressure of oxygen and the blood's greater affinity for oxygen at depth, resulting in higher blood oxygen levels and enhanced work capacity.

Threshold limit values for airborne pollutants

There is some potential for airborne pollutants to become more toxic at increased barometric pressure but, as the ambient pressure and, hence, the partial pressures of gaseous pollutants increase, so do the partial pressures of other gases in the atmosphere, including oxygen. Accordingly, the greater barometric pressure at a mining depth of 5 000 m would have limited impact on the toxicity of gaseous pollutants and only in some instances would revisions to current threshold limit values (TLV) be required, as discussed below.

Two basic laws govern the absorption of gases by blood in the lungs:

- Dalton's law states that the total pressure of a mixture of gases is equal to the sum of the partial pressures of individual gases in the mixture, and
- Henry's law states that at a constant temperature, the amount of gas that will dissolve in a liquid is directly proportional to the partial pressure of the gas at the liquid's surface.

In practical terms and within the context of present concerns, these laws imply that:

- the rising atmospheric pressure during descent in a mine would elevate the partial pressure of each gas in the inhaled air (including pollutants), according to the pressure increase and the amount of each gas present in the air, and
- the rising atmospheric pressure during descent and, hence, the increasing partial pressure of each gas present would cause more of each gas to be absorbed into the blood, with the increas in the potential for absorption of a particular gas being directly proportional to the rise in its partial pressure.

The concentration of a hazardous substance in inhaled air is the most significant variable in determining risk, and it can be variously expressed in terms of parts per million (ppm), i.e.;

- ppm as the volume of the substance per volume of air ml/m^3,
- ppm as the mass of the substance per volume of air mg/m^3, or
- ppm as the mass of the substance per mass of air mg/kg.

Alternatively, the concentration can be expressed as a percentage (%), i.e.:

- percentage volume of the substance relative to the volume of air, or
- percentage mass of the substance relative to the mass of air.

Once Dalton's law has been applied to determine the partial pressure of a gas, Henry's law can be used to predict its absorption by the blood in the alveoli. The rate of transport by the circulatory system and the amount that would be stored in a given type of tissue can then be predicted. Finally, this information can be used to ascertain the potential for adverse effects under subsequent conditions of decreasing pressure (during return to surface), in accordance with Boyle's law. The only limitation on such predictions is that some active binding occurs with certain gases, most notably O_2, CO_2 and CO, causing discrepancies between predicted and actual concentrations in the blood and body tissues (Kayle, 1999).

A given mass of pollutant per volume of air would have the same toxicity at depth as on surface and, accordingly, current TLVs expressed in mass-per-volume-terms would apply to workers in ultra-deep mines. Similarly, exposure limits and measurements based on mass-per-mass units (e.g. mg/kg of air) would also be uninfluenced by increased barometric pressure. Only where gaseous contaminants are evaluated and quantified in terms of volume-per-volume units, i.e. volumetric ppm or percentage concentration by volume, would the revision of current TLVs be necessary.

The evaluation of pressure effects on respirable dust, including its affinity for lung tissue and any pathogenic consequences, would require laboratory studies using appropriate experimental animals, conducted by a suitable medical research institution. Accordingly, it was recommended that such investigations be considered only once it is clear that ultra-deep mining is likely to become a reality (Franz,2000-b).

Managing pressure-related risks

Barotrauma

The following are seen as crucial to the effective management of pressure-related risks:

- Worker awareness of routine barotrauma risks and knowledge of preventative measures, which would be mainly behavioural in nature,
- Prospective identification of susceptible individuals by means of risk-based medical examinations (RBME) for workers in ultra-deep areas, and
- Administration of prophylactic influenza vaccinations in anticipation of seasonal outbreaks, as well as the provision of antibiotics to control secondary infections and decongestant preparations for supervised treatment of congestive symptoms.

Indications are that routine risks of barotrauma would be mainly limited to individuals with predisposing medical conditions, either chronic or acute (temporary) or, rarely, to

those with anatomical abnormalities, all of which can be prospectively identified by an RBME that focuses on the ears, sinuses and teeth, and considers the individual's medical history.

Airborne pollutants

The greater partial pressures of gaseous pollutants at working depths approaching 5 000 m and the various means of quantifying their concentration indicate that TLVs stated in terms of mass-per-volume units require no revision from current levels. However, where pollutant levels are quantified in volumetric units, e.g. ml/kg of air or per cent concentration relative to the volume of air, it would be necessary to compensate proportionally for greater ambient pressures at depth.

With regard to handheld instruments used to monitor airborne pollutants, a number of issues would need to be addressed before current devices could be confidently used in ultra-deep mines, including:

- Confirmation of instruments' operating range with regard to barometric pressure and, to a lesser extent, temperature and humidity,
- Pressure compensation and/or equalization for negative effects on instrument sensor accuracy caused by pressure changes, considering of the conditioning effect of pressure oscillations on membrane-covered sensors,
- Use of calibration procedures that cater for the prevailing barometric pressure in areas where measurements are to be made,
- Use of correction factors to compensate for pressure-induced changes in instrument sensitivity, and
- Recalibration of instruments after each underground excursion, irrespective of any correction that may have been applied during previous calibration procedures.

A possible strategy to obviate the need for measures summarized above would be to establish charging and calibration bays at or near the levels where instruments are to be used, which would also provide a number of practical advantages, viz.:

- Eliminate the need to compensate for differences in pressure between surface and the level of intended measurements or to apply correction factors where compensative calibration procedures are not used,
- Extend the service life of sensors by reducing their exposure to pressure oscillations, particularly in the case of membrane-covered sensors, and
- Provide ready access to instruments by underground personnel, for unplanned or ad hoc follow-up measurements.

Should economic considerations weigh in favour of proceeding with ultra-deep mining, a prospective laboratory investigation should be made into the risks from exposure to respirable dust at increased pressure to determine its affinity for lung tissue and any pathogenic consequences.

Conclusions

Present knowledge indicates that pressure-related effects on mineworkers' health would be moderate and limited to individuals with predisposing medical conditions, of which chronic cases could be identified through risk-based medical examinations and then managed, while acute conditions could either be prevented through prophylaxis or treated symptomatically.

With regard to airborne pollutants, a prospective investigation into exposure to respirable dust at greater pressure should be considered once indications are that ultra-deep mining is likely to proceed, as this would require an extended study entailing the use of laboratory animals. Concerning gaseous pollutants, downward revision of TLVs expressed in volume-per-volume terms would be necessary, but current mass-per-volume limits would remain valid. Gas-monitoring instruments should be confirmed as suitable or modified for use at the pressures anticipated, and revised calibration or deployment procedures would be required to minimize the effects of pressure oscillations on sensor accuracy.

Such measures would serve to minimize pressure-related impact on workers' health, thereby enhancing the productivity and profitability of ultra-deep mining operations.

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Fluorspar market recoverin from phasing out of CFCs

New report analyses fluorspar supply and demand worldwide

The early years of this decade have seen a gradual growth in world demand for fluorspar as well as significant price rises for acid-grade material, according to a new report from market analyst Roskill. Overall requirement for fluorspar is expected to rise to 5 Mt by 2030 and acid-grade will account for around 3.5 Mt of this total, which represents an average annual growth rate of just under 0.5% pa for fluorspar as a whole.

The Economics of Fluorspar (9th edition, 2005) explains that the market is recovering from the impact of the phasing-out of chlorofluorocarbons (CFCs) and is responding to their replacement by more ozone friendly and also more fluorspar-dependent products. Production of fluorspar fell to a low of 3.6 Mt in 1994 following the restrictions imposed by the Montreal protocol on the use of chlorofluorocarbons, particularly in refrigerant gases, aerosol propellants and foam-blowing agents. Production has not yet recovered to the peak of 5.48 Mt reached in 1989 but in the past ten years there has been some stabilization and recovery of world demand.

Development of new fluorspar mine operations

With the rapid reduction in world output in the early 1990s there was considerable rationalization of production and many mines closed. However, the recent fall in exports of fluorspar concentrates from China and the envisaged modest growth in the market has resulted in some increases in production in Mexico, Mongolia and Iran.

There are several proposals for new mine operations, most particularly from the Nui Phao deposit in Vietnam, which could add 220000 tpa to global supply by 2006. There are also proposals to open a new operation in Western Australia, and to re-open the Burin mine in Newfoundland, Canada. Development of new resources may be encouraged by the increases in the price of acid-grade fluorspar since the beginning of 2003.

Chemical industry is main fluorspar user

The chemical industry is the largest user of fluorspar. Some 1.8 Mt were consumed in this sector in 2003 with 50% used in the manufacture of fluorocarbons, mainly for refrigerants and foam blowing, and the remainder into other chemical applications such as PTFE and other fluoropolymers, petroleum alkylation, glass and a range of medical, agricultural, metallurgical and other applications. Demand for fluorspar in the manufacture of fluoropolymers and fluoroelastomers is strong and is likely to grow at over 5% pa in 2005 and 2006.

Replacement fluorocarbons

The chemical industry still uses nearly 1 Mtpa of fluorspar in the manufacture of fluorocarbons for refrigerants and foam blowing. Replacement fluorocarbons, HCFCs and HFCs, require more fluorspar in their manufacture, but this is now being offset by further restrictions, as several of these compounds have been seen to exhibit global warming potential. These further restrictions and the phasing out of CFCs in China over the next few years will limit growth in this market sector to around 1% pa.

Prices

Acid-grade fluorspar prices were low throughout the 1990s as a result of the rapid decrease in world demand coupled with a surge in exports of low-price concentrates from China. Following the closure of a number of mines and the introduction of anti-dumping measures against Chinese acid-grade fluorspar imports into Europe and to Mexico, the supply/demand balance began to normalize.

The Chinese government has introduced a system of export quotas and tariffs, which further helped to stabilize the market in the late 1990s, and prices recovered. By 2004 the average value of imports from China was at the highest level since 1990. At the beginning of 2005 the quoted price for fluorspar cif US ports had reached US$225-235/t.

The Economics of Fluorspar (9th edition, 2005) is available at £2100/US$4200/EUR3675 from Roskill Information Services Ltd, 27a Leopold Road, London SW19 7BB, England. Tel: +44 20 8944 0066. Fax: +44 20 8947 9568. E-mail: info@roskill.co.uk. ◆