

Air and Particulates in Underground Oil Shale Mine

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Particulate matter (PM) in the context of underground mining results from various operations such as rock drilling and blasting, ore loading, hauling, crushing, dumping, and from diesel exhaust gases as well. These operations result in the formation of fine particles that can accumulate in the lungs of mineworkers. The lung deposited surface area (LDSA) concentration is a variant solution to evaluate potential health impacts.

particulate matter

oil shale mining

lung deposited surface area

1. Air Quality in Underground Mines

The origins of particle emissions in underground mines are mining activities, diesel engine vehicles, and blasting operations [1][2][3][4]. Dust concentrations depend on mining activities [5], and can contain crystalline silica that can cause silicosis, lung cancer, and other diseases of the respiratory system [6][7]. The issue of air quality has consistently been a matter of great concern because the dust generated during mining seriously affects the quality of underground air and worker health [8][9]. The authors state that most of the studies prefer to neglect the assessment of air quality in underground mines, confining themselves to the analysis and forecasting. However, the unique conditions of underground mines, with their increased concentration of gases and solid particles, make it urgent to apply the air quality index (AQI) for effective monitoring and maintenance of safe working conditions.

Significant emphasis should also be placed on the assessment of particulate matter (PM) concentration in underground mining operations [10]. A number of studies used various measurement tools and methodologies to determine the concentration of PM in underground mines. In a study conducted by Saarikoski et al. (2019) [11], an underground chrome mine revealed a significant influence of the location and time intervals of measurements on the number and mass concentration of particle matter. For measurements, an optical particle counter was used in various parts of the mine. It indicated that PM_{10} varied from 22 to $1100 \mu\text{g}/\text{m}^3$, the total number of concentrations varied from 1.7×10^3 to $2.3 \times 10^5 \text{ cm}^{-3}$, and the ore crushing process creates dust with particle sizes over $2.5 \mu\text{m}$. At the same time, in the Saarikoski et al. (2018) [3] study, the average concentrations of particles in a chrome mine were measured, and this value was $2.3 \pm 1.4 \times 10^4 \text{ cm}^{-3}$. The distribution of the number of particles by size varied in the range from 30 to 200 nm, but the most common sizes were less than 30 nm. As an alternative for assessment, the properties of solid particles and aerosols in underground mining environments could be assessed by scanning electron microscopy and energy dispersive X-ray spectroscopy (SEM-EDS) analysis [12][13][14].

2. Lung Deposited Surface Area

The combustion of diesel is the main source of the toxic gases and particles in underground mines. When underground miners, particularly truck drivers, continuously breathe contaminated air for a prolonged period of time, severe occupational disorders may develop. In addition to toxic gases, diesel engines also release ultrafine particles (UFPs) with a size of less than 0.1 μm . Their accumulation in the respiratory system is hazardous and can result in severe respiratory illnesses [15]. When evaluated in various environmental circumstances, the lung deposited surface area concentration (LDSA) approach was successful in recognizing UFP [16][17][18][19][20][21]. Salo et al. (2021) [22], using ELPI+ in a chrome underground mine, found that LDSA concentrations vary from 137 to 405 $\mu\text{m}^2/\text{cm}^3$. The optimal particle size to estimate the LDSA distribution was no more than 100 nm, except at the blasting site, where the particle sizes were closer to 700 nm. Jafarigo et al. (2023) [23] showed that the average concentration of LDSA was relatively high ($4 \times 10^3 \mu\text{m}^2/\text{cm}^3$), while the majority of particles had a size of less than 100 nm. Afshar-Mohajer et al. (2020) [16] monitored the concentration of inhaled particles in the four main technological divisions of a taconite mine, crushing, dry and wet milling, and granulation, to measure particles smaller than 300 nm. The results showed that the average LDSA concentration was highest during the granulation process, at $199 \pm 48 \mu\text{m}^2/\text{cm}^3$. In other mining areas, the concentration ranged from 80 to 200 $\mu\text{m}^2/\text{cm}^3$. In addition, the taconite mine LDSAs in crushing and pelletizing operations were $142 \pm 52 \mu\text{m}^2/\text{cm}^3$ and $200 \pm 48 \mu\text{m}^2/\text{cm}^3$, respectively.

UFPs can carry a high concentration of toxic substances, and therefore, they can cause inflammation through oxidative stress responses, atherosclerosis, an increase in blood pressure, and even myocardial infraction [24]. The LDSA is a different method of describing particle toxicity. The challenge with current mass-based exposure limits is that they fail to account for ultrafine particles (less than 100 nm), which have negligible contributions to particle mass, but can penetrate deep into human airways, lodge in lung alveoli, and have high toxicity contributions. This is especially concerning because most diesel engine particle emissions (measured by number) fall into the ultrafine range [17]. In distinct metropolitan contexts, LDSA concentrations, size distributions, and height profiles have been measured in ambient conditions [18][19][21]. LDSA concentrations have been connected to emissions from combustion sources. Afshar-Mohajer et al. (2020) [16] used a variety of measures, including LDSA, to investigate the variability of aerosol concentrations in different processing zones of a taconite mine. Huynh et al. (2018) [17] used numerous particle concentration measures, including LDSA, to investigate fine particle concentrations in six taconite mines. LDSA concentrations in their investigation ranged from 50 to 300 $\mu\text{m}^2/\text{cm}^3$ depending on the processing region. Although LDSA levels varied from station to station, Afshar-Mohajer et al. (2020) [18] also noticed the remarkable repeatability of concentration each day. The aim of this experimental sampling was to determine the exposure of the cabin operator to diesel exhaust nanoparticles.

Benedetto et al., in their study, were the first to characterize and determine the behavior of UFPs in synthetic lung fluids. The authors found a large variability in the hydrodynamic diameter, with values less than 1 nm and greater than 5 μm , and recognized aggregation and disaggregation processes in Gamble solution and artificial lysosomal fluid using dynamic light scattering. The results of their study proposed an interaction between nanoparticles and lung fluids, particularly within the alveolar macrophage region. [25]. Kalaiarasan et al. concluded that respiratory

deposition doses and particle number concentrations can be applicable to investigate relationships between particle diameter and deposition in the different regions of the lungs, considering the impact of the UFP deposition in the deeper region of the lungs [26].

A notable Issue arises from the observation that a majority of the particles generated in coal and oil shale mines have a finely dispersed nature, enabling their infiltration into the respiratory system [27][28]. Thus, the LDSA indicator can be used to determine the potential places of deposition of particles in the lungs and to study the impact of inhaled particles on humans [29]. A number of researchers measured the LDSA in underground mines using a variety of measuring instruments in their research. Salo et al. (2021, 2023) [22][30] studied the distribution and concentration of LDSA in various places of a chrome underground mine using an electrical low-pressure impactor (ELPI+), and evaluated the possibility of using sensors to measure this indicator. The author stated that the environment around the sensors was complex because the particle sizes often exceeded the optimal range (20–300 nm), and dust accumulated inside the devices. Studies conducted in different underground mines confirm the high concentration of fine particles. These results highlight the need for enhanced monitoring of mine air quality to protect workers' health and ensure safe working conditions.

3. Oil Shale Particulates

According to Wang, Liu, and Gratt (1985) [27][28][31][32], coal and oil shale mines are significant sources of dust particles in the mining environment, and their detailed study in the context of composition, size, and monitoring methods is of particular interest. In underground coal mines, dust includes the smallest particles, and this dust consists mainly of particles containing carbon, heavy metals (arsenic, mercury, lead, etc.), and other pollutants that can lead to serious diseases of the respiratory tract of mine workers [32]. Chang and Xu (2017) [33] and Widodo et al. (2023) [34] claimed that in coal mines, especially with improper ventilation, the formation of explosive mixtures of dust and gas is possible, which increases the risk to workers. A study on the measurement of dust concentration in a coal underground mine was conducted by Jin et al. (2023) [35] and showed that it ranges from 3.4 to 106.2 mg/m³.

In comparison with coal mines, oil shale mines produce dust with a different composition [27][28]. According to the authors' study, oil shale dust contains minerals such as quartz, gypsum, and mica, as well as various chemical compounds associated with oil and gas production processes (kerogen, lead, cadmium, etc.). Typical oil shale mineral parts chemical composition consists of SiO₂, Al₂O₃, Fe₂O₃, TiO₂, CaO, MgO, SO₃, K₂O, Na₂O, P₂O₅, and kerogen oil with an elemental composition H, C, S, N, and O [36][37]. As an unconventional resource, oil shale is widely distributed around the world and has a very high potential; however, industrial mining produces it only in China, Estonia, and Brazil [36][37]. For this reason, there are only a few studies related to oil shale dust compounds, and none about particulate matter or aerosol concentration and distribution in oil shale underground mines. Wang et al. (2019) [27], in their study about the explosibility of oil shale dust, argued that dust particles in oil shale have an extremely small size and fine dispersion. In the study of kinetic analysis on the deflagration characteristics of oil shale dust conducted by Meng et al. (2022) [38], the distribution of particles of oil shale dust was determined using a laser particle size analyzer called 'Mastersizer 2000'. The average particle size of two different oil shales was 15

μm and $60\ \mu\text{m}$, respectively. In studies conducted by Yu et al. (2017) [39], the particle sizes in the oil shale dust were measured using a laser diffraction analyzer with particle sizes $68\text{--}80\ \mu\text{m}$. Teinemaa et al. (2002) [40] investigated oil shale combustion fly-ash aerosols and stated the bimodal composition first maximum at $0.1\ \mu\text{m}$ (fine particles) and the second maximum around $3.5\ \mu\text{m}$ (coarse particles).

However, all of these studies on oil shale were limited to measurements, monitoring, and analysis of PM and LDSA in underground oil shale mines, and therefore focused on the air quality problems in operational faces. The aim of this research is to analyse PM and LDSA concentrations in the operational workings of the oil shale underground mine. Producing relationships between currently used PM indicators and more descriptive and innovative indicators (LDSA and PNC) determines the need to study these components. The investigation of the correlation between LDSA and PM_1 and $\text{PM}_{2.5}$ is an important part of this research because these indicators have more diverse sources, including diesel exhaust emissions and secondary aerosol formation, which might be anthropogenic or biogenic in origin [41]. Kuula et al. (2020) and Luoma et al. (2021) stated in their studies that $\text{PM}_{2.5}$ has been shown to highly correlate with BC and LDSA [18][42]. PM_{10} concentrations are dominated by noncombustion sources, e.g., dust.

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