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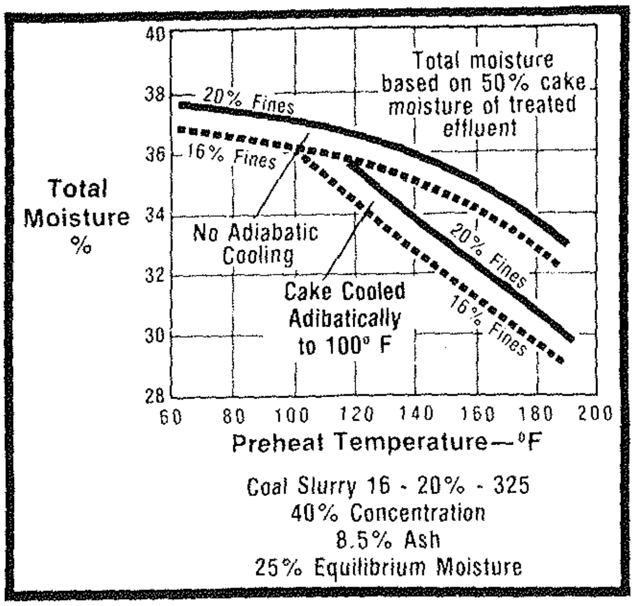

Fig. 6—Screen bowl centrifuge tests on coal slurry pipeline

Dewatering Costs
450 tph Fine Coal 28 mesh x 0 (595 microns x 0)

	Centrifugal and Thermal Dryer	Filter and Thermal Dryer
Installed Capital Costs:		
Centrifugals	$6,600,000	$ —
Filter	—	4,760,000
Thermal Dryers	8,500,000	13,910,000
Total	$15,100,000	$18,670,000
Annual Costs:		
Fuel at $1.20/10⁶BTU	$1,590,000	$2,080,000
Maintenance	580,000	545,000
System Horsepower	3,326,000	4,129,000
Depreciation (15 yrs.)	1,006,000	1,244,000
Total	$6,502,000	$7,998,000

Capital Cost Savings: $3,570,000
Annual Cost Savings: $1,496,000

1981 Basis

Fig. 7—Cost comparison of centrifugal vs. filtration system, equivalent moisture basis

Dewatering costs should also be compared for systems achieving an equivalent product moisture. The first cost of the centrifuge to dewater a coal to 15% surface moisture might be substantially higher than a disc filter producing a 20% moisture cake. If, however, thermal drying costs are added to the filtration approach to provide a cake with the same moisture as the screen bowl centrifuge, the cost comparison becomes much more meaningful. Figure 7 summarizes this approach in an analysis prepared by an independent West Coast engineering firm for a proposed customer plant expansion.

Conclusion

Today's screen bowl centrifuge represents a steady evolution from the early designs that were presented in the 1960s. With the development of improved abrasion protection, maintenance costs have been reduced. Ongoing programs with new construction materials will continue to improve overall performance. Operation and maintenance studies have shown typical costs to range from 40¢-50¢ per ton of product. The versatility of the screen bowl centrifuge permits wide variations in feed concentration and particle size that can be effectively dewatered. Of primary importance, the development of the long bowl, high speed design has provided a machine that can offer extremely high recoveries of fine feed solids while maintaining a four to six percentage point decrease in product moisture compared to alternative systems. □

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Atmospheric Fogging in Underground Mine Airways

A.D.S. Gillies and M.A. Schimmelpfennig

Abstract—*Loss of visibility due to the occurrence of atmospheric fogging in underground mine airways can lead to longer travel times and loss of production efficiency, an increase in the frequency of vehicular and foot traffic accidents and difficulty in checking rock surfaces for instability and loose material. Where hot and humid surface air meets colder underground air, conditions for fog formation may be present. Further, suspended particulate matter from diesel exhausts or stoping operations together with slow movement of air along passageways may contribute to formation. This study describes an investigation being undertaken with the cooperation of Kennecott's Ozark Lead Co. to identify causes of the problem.*

Introduction

The occurrence of atmospheric fogging in underground mine airways leads to a loss in visibility and consequent impedance to

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production efficiency. The formation of fogs in mine stoping areas and traveling ways creates difficulty in checking rock surfaces for instability and loose material and can lead to longer travel times and an increase in the frequency of vehicular and foot traffic accidents.

When hot and humid surface air meets colder underground air, conditions for fog formation may be present. Ground water inflow to underground openings and wet mining conditions increase humidity levels in the mined environment and exaggerate the problem. Suspended particulate matter from diesel exhaust or stoping operations in conjunction with slow movement of air along passageways may contribute to fog formation.

Low levels of visibility resulting from fogging have been recorded on occasions at all operating mines within southeast Missouri's Virburnum Trend lead deposits. Ventilation conditions that lead to formation are being studied in an investigation being undertaken with the cooperation of Kennecott's Ozark Lead Co.

Background

As the world's leading producer of lead, new mine production in the US amounts to 522 kt/a (575,000 stpy). About 90% of this mining activity occurs in Missouri. Most of that is concentrated in the Viburnum Trend lead deposits.

Fog formation has been reported at various times in the ventilation system of all operating mines. Within the trend total ore production is presently at a level of about 35 kt/d (38,200 stpd). Individual mines vary in production capacity from 3.8 kt/d (4,200 stpd) to 7 kt/d (8,000 stpd).

Occurrence of Underground Atmospheric Fogging

While the occurrence of fogging can be observed at all times of the year, it is most prevalent in the summer months from May to September. At worst, the fogging in the air reduces visibility to almost zero and leads to the probability of men losing orientation in familiar areas of the underground workings.

At the different mines, fog is found to occur under conditions of hot and humid surface air; near intake shafts as outside air meets slow moving, saturated underground air; in stopes where mining machines emit diesel exhaust particulate matter or dust from rock breakage or movement is present; along underground truck haulage roads, and particularly where these roads carry slow moving air from stoping operations; and where large vertical profile air temperature differences occur between the mining area back (roof) and floor.

All mines reported that fog problems build up as the mining cycle progresses through the day, and through the week. After periods of production shutdown such as weekends, there is clear air in most underground sections where perceptible air movement is present. However, visibility deteriorates as the production cycle is set in motion.

Moisture necessary for fog formation comes from three major sources.

- Humidity carried into the mine by intake air. This is at the highest level in summer and fog that forms when the outside air reaches saturation on contacting cold underground air can extend 1.5 km (5,000 ft) down drifts leading to stoping areas. The underground air remains at a high relative humidity condition and at other points through the mines where temperature gradients occur, fogs can be present.
- Ground water from surrounding strata flows (or drips) into mined areas. Large standing pools of water on the mine floor allow high humidity pick up when present. One mine that claims to have the least severe fog problem in the area, has lowered the surrounding water table over a number of years. This mine is so dry that on occasions in winter trucks must spray to keep roadway dust down.
- Water emitted from machinery operation. Large machinery is diesel powered. A product of combustion is water. Further, water sprays are used on some machinery for scrubbing exhausts. Some stationary machinery in stopes has water added to the exhaust for cooling. Compressed air used to power many of the mines' drills carries large quantities of water (particularly in summer). The expanding air exhausting from the machines generates considerable condensation.

Particulate matter in the air that may act as condensation nuclei is derived from suspended products of combustion in diesel exhaust; roadway dust from vehicular traffic; dust from use of explosives for rock breakage; dust from other stoping operations and, in particular, drilling, rock loading, and rock dumping; and dust at points of rock crushing.

Direct Cost of Mine Atmosphere Fogging

Direct action taken by the various mines to reduce or eliminate the problem and ensure a minimum safety hazard includes the following.

- Air velocity is increased through the mine openings during all or part of the year. One mine has an extra 375 kW (500 hp) fan pulling air through a section that previously had presented problems. This operates during summer at a power cost of $4,000 per month. Another mine has an additional 150 kW (200 hp) fan operating for this purpose.
- Rerouting of air through active mine sections to increase air velocity. Where air flow velocity can be increased to 0.25 m/s (50 fpm) through the large underground openings, little problem of fogging has been recorded.
- Truck-traveled roadways are marked with reflector strips on side pillars or a line is painted on the mine back to aid drivers.
- Trucks are scheduled to drive at slower speed in areas of bad fog. The reduction is determined by visibility loss but typically, trucks that normally operate at 30 km/hr (20 mph) are restricted to 15 km/hr (10 mph) when visibility is at 50 m (150 ft) and down to 5 km/hr (3 mph) when it deteriorates to 10 m (30 ft). Increased travel times lengthen the production cycle and at times lead to payment of overtime to make up for lost production.

Related Safety Problems

Restricted vision causes a potential problem. The potential for vehicular collision and the danger to foot traffic on roadways is apparent. Some labor relations problems have been experienced by several of the mines as men have at times been unwilling to drive trucks in problem areas. Accidents that can be tied directly to the presence of fog have occurred. In one mine a personnel carrier ran into the back of a truck. In another, a tractor was damaged after making an improper turn. Frequent traffic accidents as a result of vehicles running into the side of pillars have been recorded.

Lack of visibility hinders checking the mine back and sides for structural instability and loose rock. In many sections of the various mines the mined space is 20 m (60 ft) high and at times 30 m (100 ft). Necessary checking, when visibility is reduced, is extremely difficult.

Further, quality of the work environment is reduced in the presence of fog with the possible effect on men underground of a closed-in feeling, disorientation, and dampness. The association of fog to "smoke" from diesel engine exhausts has led to recorded worker complaints. This deterioration in the environment can have a detrimental effect on safe and efficient work habits.

Theory of Fog Formation

Fog formation in an atmosphere will occur under conditions in which moisture in the air-vapor mixture becomes supersaturated and in the presence of condensation nuclei of appropriate size, shape, and chemistry. Supersaturation will only occur with a moisture vapor pressure increase or decrease in the atmospheric temperature. Under normal conditions, condensation nuclei must be present to serve as deposition surfaces for water droplets although under rigid experimental control using an artificial atmosphere Amelin (1967) states that fog generation has occurred. In the mine atmosphere both liquid and solid particles in suspension can serve as condensation points. Possible particle sources include dust from drilling and blasting, machinery exhaust from diesel units, rock crushers, and roadway dust generated from vehicular movement.

In making a classification of particulate matter occurrence by size, as has been used in Fig. 1, Ross (1972) states that the term Aitken nuclei is used for those smaller than 0.1 μm. For these, behavior is explained by Brownian motion—particles are so small that continual collisions with atmospheric molecules means that they never settle out of an air mass. Both Ross and Mercer (1973) have found that when these Aitken nuclei collide with one another, or with other particles, they often adhere together. This is coagulation. Rogers (1976) states that although these small Aitken particles can be measured to have high concentration levels in a standard atmosphere, these levels are not thought, in themselves, to lead directly to fog formation. However, Ross maintains that the chemical make up of the Aitken particles can affect the stability of a fog. This can occur when the particles adhere to water droplets already present.

Green and Lane (1957) refer to the larger particle sizes of 0.1-1 μm as the major condensation nuclei source. It is this size that are responsible for the majority of surface atmospheric fog formation. They note that these large particles in the atmosphere are found at a concentration level of 100 to 1000 times less than that of the Aitken nuclei. Surface air will contain in the order of 10,000 Aitken nuclei per cm^3, but a concentration of large particles of 5 to 200 per cm^3 under normal conditions.

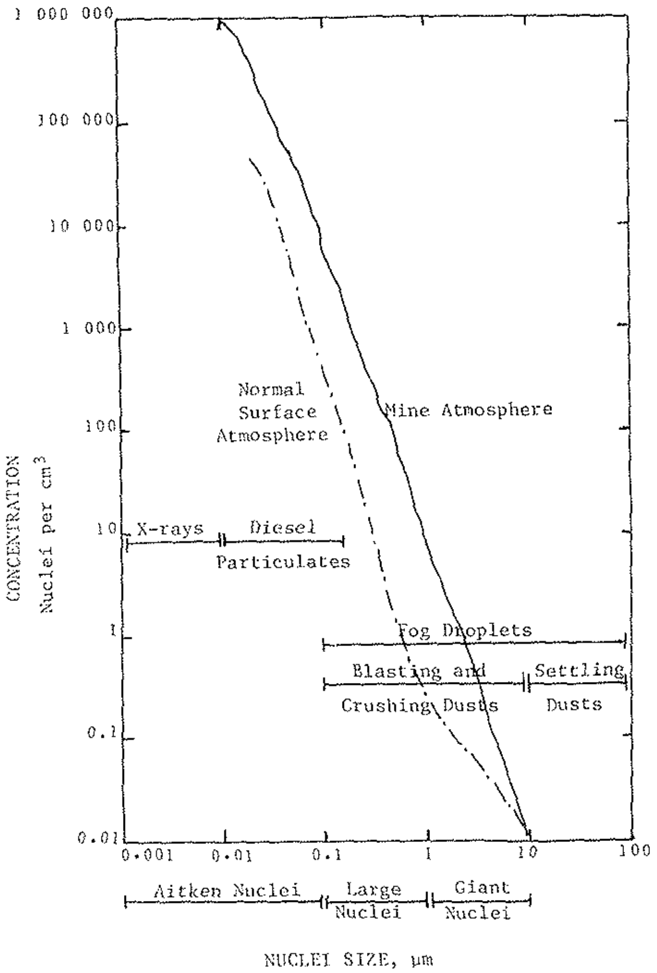

Fig. 1—Concentration of atmospheric nuclei against size for normal surface air (from Green and Lane) and mine air. Size ranges for particulate sources and nuclei types are shown.

The giant atmospheric particles, or those of size greater than 1 μm are also, to some extent, responsible for initiation of fogging. However, the concentration of these nuclei at normal surface conditions has been measured to be approximately 1/cm^3, and so they do not have the same influence on fog formation as do the particles of size 0.1-1 μm. Hartman (1961) notes with respect to giant particles that the fraction of size greater than 10 μm will usually settle out of the air in a short period of time, and so are not present to play a part in fog formation.

For moisture supersaturation conditions to be present, Amelin states that one or more of the cooling influences of adiabatic expansion, heat loss through radiation, introduction of an outside cold gas stream, or contact with a cold surface must affect the vapor-gas mixture. Furthur, vapor pressure can be influenced by other processes such as chemical reactions occurring between mixing gases, photosynthesis, or radiation activity.

In most underground situations, abundant free water is available on mine surfaces and air saturation can be easily achieved. Examination of test data compiled in Tables 1, 2 and 3 shows that measured wet and dry bulb temperatures are seldom more than 1°C apart. Relative humidity of the mine atmosphere is normally about 90% and the air vapor mixture is approaching a near-saturated situation. In these prevailing conditions, fog formation will occur with a slight decrease in air temperature, or increase in vapor pressure leading to vapor supersaturation in conjunction with the presence of high concentrations of large or giant sized condensation nuclei.

The Ozark Lead Co.

The Ozark Lead Co is located at the southern end of the Viburnum Trend line of mines. The mine workings are extensive. Mining occurs in 3 m (10 ft) to 40 m (130 ft) zones within the Bonneterre dolomite formation and stopped out areas vary in width from 150 m (500 ft) to 250 m (800 ft). A multi-level system of room and pillar mining is practiced. Following drilling and blasting operations, ore is removed by load-haul-dump vehicles or truck haulage. These diesel-powered units send rock through ore passes to a lower transport level where a diesel-powered rail system is in operation. Mining rooms are advanced on a face 10 m(30 ft) wide. Back height varies in different parts of the mine from 3-10 m (10-30 ft) and may reach 20 m (60 ft) along some haulageways.

Diesel equipment is used exclusively in the mine, with 110 units underground with total rated power of 8800 kW (12,000 hp). The mine is wet, with about 100 L/s (1,600 gpm) of water being pumped to the surface.

Mine ventilation is through three downcast and two upcast shafts. Flow is initially directed through active mine workings and then by ore passes and inclined roadways to the haulage level before being exhausted from the mine. Underground auxiliary fans, tubing, and doors are used to assist distribution and control flow of air.

Test Airways

The three underground areas where test data was collected are described as follows.

- Area J-3 is located in the west section of the mine along a roadway. The study area begins approximately 150 m (500 ft) from a crusher used to crush waste rock for use on roadways. The length of the study area is 500 m (1,600 ft).
- Area G-3 is located in the east section of the mine. This study area begins approximately 50 m (150 ft) from a 30 kW (40 hp) fan in a sloped narrow airway. Approximately 75 m (240 ft) along the study area, the airway widens, then is pinched off near the end of the study area. The study area is 200 m (650 ft) in length.
- Area D-2 is also located in the east section of the mine, but at an elevation approximately 30 m (100 ft) higher than area G-3. The area is a narrow roadway approximately 175 m (550 ft) in

length. The study area begins near an ore pass and ends approximately 200 m (650 ft) from an active stope. There is a 30 kW (40 hp) fan 100 m (330 ft) from the end of the D-2 study area.

Air velocity was obtained by using a vane anemometer or smoke tubes as appropriate. Wet and dry bulb temperatures were recorded with the use of sling psychrometer. An electronic solid state LCD thermometer was used to accurately record air temperature where fog layering was observed.

The concentration of condensation nuclei was recorded with the use of two particle analyzers. The concentration of large and giant nuclei was measured by use of a Royco aerosol particle monitor while an estimation of the concentration of submicron sized particles was found through measurement with a Gardner small particle detector. Visibility was measured by determining the distance that an observer could detect a man covered by dark cloth with the observer's cap lamp shining on the man. The man had his cap lamp extinguished, and no other lighting was present in the area for correct visibility measurement.

Results

Data recording characteristics of mine fogging have been gathered over a number of visits to the Ozark Lead Co. Some examples of observations are recorded in Tables 1, 2, 3, and 4. Test measurements are compiled in a form such that air temperature, velocity, visibility, and air-borne particulate concentration can be assessed simultaneously for observations at the same point in an area.

Interpretation of Mine Data

Test results from measurements taken both on the mine surface and underground allow comparisons to be made and some speculation as to the cause of mine fogging.

Aitken Nuclei

The measured concentration of particulates in the mine has been found to be much greater than that on the surface. The impact of this difference can be seen in Fig. 1. Amelin (1967) states that the average surface atmospheric concentration of Aitken nuclei is 10,000 per cm^3 with measurement levels ranging from 3,000-50,000 nuclei. Readings taken on the surface of the mine property gave an average level of 4,200 nuclei per cm^3 while average underground readings have been calculated to be 136,000 nuclei per cm^3. Further, local concentrations underground were recorded to a maximum of about one million nuclei per cm^3. The highest readings being found in air near where diesel equipment was operating. In Table 4, concentrations are shown.

Evidence that diesel emissions are sources of Aitken nuclei has been found by both Stefanko, Ramani, and Kenzy (1977) and Carlson and Johnson (1979). While high Aitken nuclei levels do not directly lead to fog formation, their presence and ability to adhere to water droplets, or to each other, and coagulate to form large active condensation nuclei will indirectly influence fogging processes. Green and Lane (1957) support this conclusion and reason that the rate of coagulation of particles will increase with higher concentrations of the Aitken nuclei. Two factors influence coagulation; the probability of occurrence of collisions and the physical and chemical properties of the particles themselves. The nature of the particulates determines whether or not vapor will be absorbed. This in turn influences whether or not the particles will stick together if collisions take place.

A search of literature has turned up a lack of evidence to explain the behavior of Aitken nuclei in mine atmospheres in respect of the nature of coagulating influences on these particles.

Table 1—Measurement Test Data Collected September 10, 1981 at Ozark Lead Co. Mine

Test Area	Temperature °C w.b.	Temperature °C d.b.	Air Velocity m/s	Visibility m	Aitken Nuclei[1] per cm^3 0.3 m above road grade	Aitken Nuclei[1] per cm^3 1.5 m above road grade
J-3 point I	19	19.25	0.25	45	120 000	105 000
point II	—	—	—	—	—	—
point III	18.5	19	0.1	38	525 000	210 000
D-2 point I	20	20	0.2	39	710 000[2]	500 000[2]
point II	20	20	0.2	48	240 000	220 000
C-3 point I	19.5	19.5	2.0	61	270 000	135 000
point II	19.5	19.5	0 to 0.1	48	255 000	131 000
Surface	19.5	26	—	—	2950	

[1]Aitken Nuclei readings reflect the average of five readings
[2]Reading was affected by diesel equipment in vicinity

Table 2—Measurement Test Date Collected September 22, 1981 at Ozark Lead Co. Mine

Test Area	Temperature °C w.b.	Temperature °C d.b.	Air Velocity m/s	Visibility m	Aitken Nuclei[1] Per cm^3 0.3 m above road grade	Aitken Nuclei[1] Per cm^3 1.5 m above road grade
J-3 point I	20	20	0 to 0.1	15	155 000	138 000
point II	—	—	—	—	—	—
point III	19.5	19.5	0.33	19	995 000	510 000
D-2 point I	20.5	21	0.25	25	365 000	345 000
point II	20	20.5	0.2	25	105 000	107 000
G-3 point I	19.5	19.5	1.43	39	130 000[2]	345 000[2]
point II	19	20	0.2	38	180 000	205 000
Surface	15	18	—	—	5400	

[1]All Aitken Nuclei data reflect the average of five readings
[2]Reading was affected by diesel equipment in vicinity

While results from the Ozark Lead tests give little information on coagulation of Aitken nuclei, they return strong evidence that the nuclei attach to individual moisture droplets once fog formation has begun. From results set down in Table 2, it can be seen that in area J3, visibility at point I was measured at 15 m (50 ft) while at point III it was at 19 m (60 ft). However, the Aitken nuclei average concentration at the high visibility point was measured to be five times that at point I. Aitken nuclei are so small that they are invisible to the eye. As these particles are too small to settle out of the air, the low Aitken concentration at the point of dense fog must indicate that these particles have attached to the available moisture droplets in the fog. As further evidence, results in Table 3 show that in area J3, at point II a difference in visibility of 4 m (10 ft) was found between readings taken one hour apart. However, as the density of fog increased, the Aitken nuclei concentration decreased from 205,000 per cm^3 to 80,000 per $cm.^3$.

In these two cases, a decrease in Aitken nuclei concentration of about 500 and 250% respectively has been measured while a substantial increase in fog intensity was being observed. As the only physical change in the atmospheric system taking place was the increase in fog forming moisture droplets, evidence of attachment of nuclei to the available droplet surfaces is provided.

In summary, it is considered that Aitken nuclei are formed in the underground atmosphere predominantly from diesel exhaust emissions. They probably do not enter directly into the fog formation process, although more research is needed on this topic to ascertain if Aitken nuclei have any inclination to coagulate to form larger particles. Aitken nuclei attach to fog droplets and may affect the growth or dispersion characteristics of the fog after formation.

Large and Giant Nuclei

Large condensation nuclei (0.1 to 1.0 μm in size) have a surface atmospheric concentration level of 5 to 200 per cm^3. It is these particles and those of giant size (1.0 to 10.0 μm) that form the major source of condensation surfaces for fog forming moisture droplets. The Royco Particle monitor used in the study can detect particles in the range 0.5 to 15.0 μm, and so has limitations for counting particles at the lower end of the large particle range.

In surface atmospheres, a count in the large particle size range, 0.5 to 0.7 μm of two or three per cm^3 is considered normal. Results in Table 3 for the underground atmosphere in area J3, point II and point III show average condensation nuclei concentrations for this size range of 6.1 and 12.7 per cm^3. Qualification is necessary in the interpretation of these results. In both these areas, fog was thick with visibility at or less than 26 m (80 ft). Amelin (1967) states that under fog conditions at these levels, there may be a fog droplet density of 50 to 600 per cm^3 in the air. The Royco instrument may have been giving counts of both condensation nuclei and some already formed droplets and so leading to distortions in the particle count measurements.

Atmospheric fogs normally have a mean droplet size of 7 to 15 μm. The higher particle size ranges measured by the Royco instrument are at or near this level; particle concentration readings were off scale (the Royco instrument can only measure up to a maximum concentration of 35 per cm^3) in these ranges indicating that the instrument was probably detecting some fog droplets.

While it is difficult from these results to give a reasonable estimate to the particle count in the mine atmosphere for giant particles, some speculation can be made as to the concentration of large particles at the low end of the size range. The particle size ranges of 0.5 to 0.7 μm and 0.7 to 1.4 μm are significantly outside the mean fog droplet size mentioned earlier. From the results in Table 3, it can be seen that average concentrations were measured for these size ranges from 6.1 to 12.7 per cm^3. It can be reasoned that some of the increase in the concentration levels above that normal for surface air is due to a higher particle concentration in the mine air, and some results from distortions caused by the counting of fog droplets. It should be noted that determinations with the Royco instrument for these size ranges were made as the first readings for the day and so it is probable that they were not as affected by high humidity as later measurements. While this supports the contention that the mine air particle concentration level for the size ranges is greater than that normal at the surface, considerably more experimental observation is needed for confirmation.

Table 4—Increase in Aitken Nuclei When Diesel Equipment was Operating Nearby

Concentration of Nuclei Without Diesel Operating Nuclei per cm^3	Concentration of Nuclei With Diesel Operating Nuclei per cm^3	Percent Increase
78 000	450 000	580
110 000	310 000	280
165 000	440 000	270
175 000	1 700 000	970
150 000	390 000	260

Average Percent Increase—470
Average Concentration Without Diesel—136 000
Average Concentration With Diesel—658 000

Air Temperature and Velocity

Atmospheric air temperature and velocity influence fog formation. From observation it would appear that a fogging situation rarely develops underground over a significant area where the air velocity is maintained above 0.25 m/s (50 fpm) and if a fog is present at that level it will not be as heavy as that present with less air movement. At the high air flow rates, both

Table 3—Measurement Test Data Collected September 29, 1981 at Ozark Lead Co. Mine

Test Area	Temperature °C w.b.	Temperature °C d.b.	Air Velocity m/s	Visibility m	Aitken Nuclei[1] per cm^3 0.3 m above road grade	Aitken Nuclei[1] per cm^3 1.5 m above road grade	Large and Giant Nuclei per cm^3 Size Range · μm 0.5-0.7	0.7-1.4	1.4-30	3.0-5.0	5.0-15
J-3 point I	20.5	21	0 to 0.1	25	390 000	145 000					
point II[2]	19.5	20	0.25	25, 21[3]	210 000, 80 000[3]	200 000	6.1	6.8	9.9	>35	>35
point III	19	19.5	0.10 to 0.12	26, 21[3]	139 000	135 000	12.7	10.4	>35	>35	>35
D-2 point I	21	21	0.2	24	180 000	201 000	—	—	—	—	—
point II	20.5	20.5	0.25	22	160 000	105 000	—	—	—	—	—
G-3 point I	—	—	—	—	—	—	—	—	—	—	—
point II	—	—	—	—	—	—	—	—	—	—	—
Surface	17	22	—	—		3450	—	—	—	—	—

[1]All Aitken Nuclei data reflect the average of five readings
[2]*Large and Giant Nuclei data collection at point II was completed at 6:00 p.m.*
[3]First readings were taken at 5:00 p.m., second readings were taken at 6:00 p.m.

evaporation of fog droplets will be promoted, and mixing with layers of different psychrometric characteristics will occur, helping to disperse the fog. During field observations a fogging situation was recorded in an area of relatively high air movement. Results in Table 2 detail that in area J3 a thick fog of 15 m (50 ft) visibility level and an air movement rate of less than 0.1 m/s (20 fpm) was observed at point I. In moving along the roadway to point III, the air increased velocity to 0.33 m/s (65 fpm) while at the same time fog dispersal was occurring and visibility level was increasing to 19 m (60 ft). Air at both points was saturated with a temperature difference between points of 0.5°C (1.0°F).

Temperature differences have been observed in areas of abrupt fog density transitions. Even air temperature differentials as small as 1.0 to 2.5°C (2° to 4.5°F) have been observed to cause significant changes. Horizontal layering of different temperature air masses has been recorded with foggy air lying above or below a layer of clear air. Transitions also occur along roadways in Table 3, area J3, a decrease in visibility level from 26 m (80 ft) to 21 m (65 ft) is seen as air travels from point I to point III and temperature decreases by 1.5°C (2.5°F). As the mine air is at or nearly at the saturation level, any temperature decrease causes moisture condensation on available particulates.

Increased air movement and mixing reduces these transition areas and decreases the likelihood of fog formation.

Possible Solutions to Mine Atmospheric Fogging

Any solution to the problem of mine fogging must direct attention to suspended particulates, air temperature, humidity, and air velocity. The proper control of any one of these quantities could eliminate the fogging process. However, the situation is complex and control of a single quantity can not be established without affecting other quantities unless rigorous laboratory control is implemented at great expense. Possible solutions toward the elimination of mine atmospheric fogging include the following.

- Heating the mine air to depress the dew point when a fog begins to form and help promote evaporation of already existing droplets and discourage the formation of new droplets.
- Chemically drying the humid air before it has a chance to develop fog droplets. It is likely this would have to be done at several points along an airway, since there is an abundance of water constantly dripping into mine airways.
- Refrigeration of air to lower the humidity would effectively control already-formed fog droplets and reduce the chance of other droplets forming.
- Use of centrifugal fan scrubbers to help maintain an air velocity of 0.25 m/s (50 fpm) and remove many suspended particulates and much of the moisture from the air.
- Using cool mine water to lower the temperature and the humidity of the air entering the mine from the surface could possibly reduce the degree to which the fog problem presently restricts visibility.
- Additional fans to maintain an air velocity of at least 0.25 m/s (50 fpm) would greatly reduce the widespread occurrence of the underground fog.

Although these solutions would either eliminate or help reduce fogging, one other important point should not be ignored. One result of this investigation showed that the Aitken nuclei produced from diesel exhaust readily attach to fog droplets. Once attached, these droplets may be very hard to disperse or evaporate, and this lends credence to the author's opinion that the level of these particulates should be controlled to help eliminate fogging and to forge a healthier work environment. Since some of these diesel particulates are in the large and giant size range and thereby serve as condensation nuclei, proper control of them may help to eliminate the initiation of fog formation. Controlling other sources of condensation nuclei (such as drilling, blasting, dumping, and crushing dusts) with water sprays or airflow will help to alleviate the fog problem. The investigation has shown that correct control of suspended particulates and the elimination of air masses with two separate psychrometric states can reduce the severity of the fog problem, and any solution should take this into account.

A summary of the six solutions given above with further explanation follows.

- Heating mine air represents a reasonably cheap method of reducing underground fog (Hartman, 1973), but due to other factors it is not an acceptable solution. Although heating the air would depress the dew point, the additional heat input to the air would allow moisture pick up along airways and raise both the wet and dry bulb temperatures. Since this would lead to a very uncomfortable work environment and would not help reduce suspended particulates or reduce the likelihood of mixing air masses, this solution is not acceptable.
- Chemically drying the air is six times more costly than heating the air (Hartman, 1961), and this process also produces heat that will allow the air to pick up moisture more easily once it passes over the drying agent. This process will not remove particulates or insure a single uniform air mass, and therefore, it probably would not be a viable solution to the problem.
- Refrigerating mine air is costly and probably represents the most expensive solution to the problem (Van der Walt, 1979). High maintenance costs and the fact that refrigeration would not remove suspended particulates or boost air velocity to help mix air masses, make refrigeration an unlikely choice as a solution to the problem of mine fog.
- Centrifugal fan scrubbers represent a medium cost alternative, and in the author's opinion, appears to be the single most feasible approach towards a solution of the problem. Fan scrubbers are fairly cheap and would remove suspended particulates and reduce the humidity level in the air (Marchello, 1974). These scrubbers would also help to boost air velocity and promote the mixing of air masses. Although more study is necessary to determine the most economical solution to the problem, scrubbers seem to offer a greater chance of successfully eliminating the problem, since they would attack the problem in three ways (i.e., reducing the concentration of particulates and the levels of humidity, and by increasing air velocity).
- Using mine water to cool air entering the underground airways would cost approximately one third as much as refrigeration and nearly the same as scrubbers (Whillier and Ramsden, 1976). Although this solution would reduce humidity levels, it would not increase air velocity or remove suspended air particulates, and therefore is not a likely solution.
- Additional fans would cost approximately one sixth that of refrigeration (Hall, 1981) and would primarily help to mix separate air masses and promote evaporation of fog droplets. While this solution would cost less than scrubbers, it would not reduce suspended particulates or reduce humidity. Economically, this solution may represent the most plausible solution, but more study is necessary to determine the full impact of fogging on production costs.

In general, any economically feasible solution to the problem will include some scheme to increase air velocity to a minimum of 0.25 m/s (50 fpm). Controlling airflow with stoppings to channel air where desired can help reduce the total fan requirement necessary for a 0.25 m/s (50 fpm) airflow velocity. Also included in the scheme should be methods to limit the possibility that particles will become airborne. Water sprays near areas where mining operations show a potential for generating suspended air particulates (including water scrubbers for diesel equipment) can reduce suspended particulates to low levels. Both an increase in airflow velocity and a reduction in suspended air particulates will decrease the chances of producing an underground fog. An increase in airflow velocity creates a psychrometrically uniform air mass and diminishes the number of potential condensation points. Finally methods to increase airflow velocity and lower the levels of suspended air particulates are relatively inexpensive when compared with methods for reducing moisture and humidity levels in the mine atmosphere.

Conclusions

The occurrence of atmospheric fogging in underground mine airways leads to a loss in visibility and consequent impedance to production efficiency. Any scheme to eliminate or reduce mine atmospheric fog must direct attention to control of air temperature and humidity, flow rate, and condensation nuclei particulates.

The study has been directed to examining the characteristics of mine air in which fog formation is likely. Abundant moisture, on mine surfaces and in ventilation flow, must be present to initiate formation, and although means are available for drying air, this is difficult and costly. Sharp air temperature transitions should be avoided in airways as they change the dew point of the mine atmosphere and can lead to formation of pockets, zones of layers of fog. A steady moving flow (0.25 m/s (50 fpm) or more) will help to keep air mixed.

The importance of airborne particulate matter in the fog formation process is affected by size range. The Aitken nuclei (size less than 0.1 μm) may play only a minor role in the initial fogging process, although later surface attachment to droplets may increase fog density. Particulate chemical properties and their ability to coagulate need to be considered and further study on these characteristics is warranted. The large and giant nuclei (size 0.1 to 10.0 μm) appear to be important ingredients in fog generation. Sources of these particles include products of blasting and dust from vehicular traffic; fog density increases with their concentration. Larger size nuclei do not remain airborne for lengthy periods and so have not been considered as a source. Diesel emission particulates are of the smallest size range, that of the Aitken nuclei, and so are not considered to directly contribute to the first steps in fog formation.

The study has attempted to identify important parameters in the initiation and formation of a mine fogging atmosphere and so contribute to an understanding of a problem affecting production efficiency in many underground mines. □

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