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# Fog mesh as an alternative fog removal method in mine ramps

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**Abstract**

*In recent years problems related to mine-air fogging have not been intensively studied. Although fogging problems have been around for a long time, they are getting worse with increased mechanization. Various methods are now being used with varying degrees of success in mines having fog problems. Due to the mixed results of these remedies, fog is often simply acknowledged as another nuisance to be accepted. Fogging problems occur in cool and temperate climates as well as in tropical climates. In Finland, fog is observed mainly in the decline, causing a safety hazard for drivers. A cool climate sets its own restrictions for choosing a fog removal method. In this study, a new approach based on the adhering characteristics and condensing aptitude of water to fog removal is considered. When humid air moves over a surface, fog droplets are attached to it, and water condenses into larger droplets. This study utilizes fabric nets having water collecting characteristics to collect fog droplets that then fall or slide down the mesh. Four materials were tested by attaching them to a testing frame developed for the purpose. The evaluation of these meshes was carried out by a set of measurements and observations. Detailed information of the testing conditions and the results obtained are given. The results received from the study are promising. They indicate a decrease in both humidity and particle concentration. In most cases air rerouting was avoided and air velocities remained essentially the same as without the mesh. The practicality of the method for use in an underground mine is considered. Costs and part-time usage of the fog removal mesh are also evaluated.*

## Introduction

Even though several fog removal methods are used in mines, none of these alternatives are flawless. Heating is problematic in hot mines, refrigeration is expensive, increasing the air velocity may be ineffective and chemically drying the air is impractical. Furthermore, water leakage prevention is expensive, especially if a wide area is to be treated.

Some fog removal complications result from the climatic conditions in Finland. Methods that have been developed for warmer climates are impractical in subarctic conditions. As most fogging is mainly observed in the declines of the mines, methods designed for use in the working levels may be unsuccessful. For these reasons, a new approach is considered.

## Fog removal methods

Many fog removal alternatives are known and have been used in mines. These methods include heating, cooling, scrubbing, chemically drying the air and increasing air velocity. Keeping air and water separated has also been practical in some cases. It is said that any solution to mine fogging must direct attention to suspended particulates, air temperature, humidity and air velocity (Tien, 1999).

At present, air heating and increasing air velocity in the area of fogging are considered the best solutions to the problem. In some references, however, air heating is criticized because it adds heat to the mine environment and does not reduce suspended particulates. Increased air velocity does not reduce humidity or dust, but it simply mixes separate air masses and is considered to promote evaporation from fog droplets. The efficiency of this method is questioned (Calizaya et al., 2002; Martikainen, 2005).

Fog removal through cooling is based on decreasing the relative humidity of air and uses either cool mine water or refrigeration. This approach is viable in warm environments, even if it does not affect particle concentration in the air. Unfortunately, refrigeration is rather expensive.

Centrifugal fan scrubbers reduce particle concentration and humidity as well as increasing air velocity. It is a medium-cost solution and is considered promising (Schimmelpfennig, 1982).

Removal of humidity by preventing water leakages is not mentioned in the literature as a fog removal method, but it can be used to some extent. Unfortunately, treating large areas of a mine in this manner is expensive. Also, due to open ditches and

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pumping stations along the decline, preventing leakages may not be effective enough for fog removal (Martikainen, 2006). Decreasing humidity by routing drier air to the foggy areas is another method not discussed in the literature. However, in some cases such changes in the ventilation system may result in fog removal. Nevertheless, water-bearing sites and water leakages pose a problem also for this method.

Chemically drying the air is not practical in mines. Though it decreases humidity, it is expensive, does not remove dust, adds heat to the air and is troublesome.

## Fog removal in Finland

**Climatic conditions and restrictions.** The climate in Finland is cool and has distinct four seasons. During summer, the air is warm and the humidity changes depending on the weather. Temperatures, especially in southern Finland, may rise to 30˚C (86°F). Spring and autumn are humid with rapidly changing temperatures. In northern Finland, temperatures as low as -40˚C (-40°F) are reached in the winter.

Heating of fresh intake air is required in most Finnish mines during the winter. Heating is accomplished through the use of direct electrical air heaters, by the use of warm water or by directing air into the mine through old stopes, where rock surfaces emit their heat to the air. To prevent freezing of the road surfaces during the winter, declines are used as secondary air exhausts. Alternately, at the deepest Finnish mine, the Pyhäsalmi mine, refrigeration is needed on the lowest levels in the summer.

**Fog removal method evaluation.** In most Finnish mines fogging is observed only in the decline. The cross-sectional area of a decline is typically so small that there is no room for fans. Thus, equipping fans with scrubbers is not a sensible solution.

Refrigeration is not considered practical as the temperature of air departing the ramp is usually already about +8˚C (+46°F) and freezing and frost should be avoided. Heating may be feasible in some cases, as heat is not a problem in most Finnish mines and definitely not in the ramps. In some mines, nevertheless, the temperature difference throughout the ramp is more than 10˚C (50°F) and heating may thus prove costly.

Usually air velocities in the decline are quite high, typically between 0.5 and 2 m/s (100 and 400 fpm), even without increasing air velocity. Despite these velocities, fogging is observed in all Finnish underground mines at least some times during spring, summer and autumn.

**Current fog removal situation.** Fog removal methods currently used in Finland are prohibiting water leakages or increasing air velocity by either rerouting air or by adding fans. Air heating has been discussed at some mines, but this has not yet been tested.

Minimizing flowing water in foggy areas has proven to be effective at the Pyhäsalmi mine, but it only helps locally. The long length of the ramps makes the method prohibitively expensive. Also, many water-bearing sites along the ramp make this method quite susceptible to failure.

Decreasing humidity by routing drier air to the foggy areas is not used in Finland. This is due to the fog occurrence in ramps, where the effect would only be local, and the usage of ramps as secondary exhausts. Also, routing fresh air straight to the exhaust would be difficult.

Increasing air velocity by rerouting has not been as effective as expected in the three mines, Pyhäsalmi, Orivesi and Louhi, in which it has been tested. Fog has been observed even with air velocities approaching 2.5 m/s (8.2 fps).

Many methods suggested in the literature are considered impractical in declines of the Finnish mines. Because none of the tested methods have yet solved the problem, developing new methods is considered the best approach.

## Theoretical background of the fog mesh

Fog formation requires high relative humidity and the existence of condensation nuclei in the air. Relative humidity is a measure of water vapor content in the air in comparison to the water-bearing capacity of that air. It can also be defined as the ratio of the partial vapor pressure to saturation vapor pressure at a given temperature. Usually the dew point temperature, a temperature in which relative humidity reaches 100%, is close to or the same as the measured temperature when fog forms.

Fog droplets form around condensation nuclei that can be either particles or aerosols. Examples of condensation nuclei include salt and soil particles, dust and pollutants. The diameter of condensation nuclei is typically about 0.2 μm, but their sizes vary considerably. These pollutants also decrease water equilibrium pressure and enhance fog formation in relative humidity as low as 70%.

The atmosphere in mine ramps is ideal for fog formation. The low temperature of the rock walls surrounding the decline creates a cooling effect. As the exhaust air moving through the ramp is saturated or near saturation, fog starts to form when the temperature decreases. Exhaust air also carries a considerable amount of dust and diesel exhaust gases that both act as condensation nuclei and decrease the water equilibrium pressure in the air, encouraging fog formation.

The method suggested here for fog removal is based on the adhering characteristic and condensing aptitude of water. When humid air moves over a surface, some fog droplets are attached to it. These droplets then grow as more water condenses. In the case of a mesh the surface area for water attachment and condensation is large. As water collects on the net, droplets join to form larger drops and fall or slide down under the influence of gravity. If the surface is cooler than the passing humid air, the water collecting effect of the surface is even more conspicuous.

## Prior use of fog meshes

Interestingly, fog meshes have already been used in other contexts than for fog removal purposes. In extremely dry areas of the world, meshes are used to collect water. Especially since the 1990s, there have been special projects with the goal of harvesting fog water in countries with dry climates (FogQuest, 2005). The initial investigations into the use of fog meshes began about thirty years ago (UNEP, 2005).

Current research suggests that fog collectors work best in coastal areas where water can be harvested as fog moves inland carried by the winds. However, the technology has also the potential to supply water in mountainous areas should the water present in stratocumulus clouds at altitudes of approximately 400 to 1,200 m (1,300 to 3,900 ft) be harvested.

With these fog meshes, the fresh water is sought after and collected for further use. Walls are built similarly to cover large areas and to allow air to pass through them. Typically, nylon or polypropylene is used as a collector material.

The potential for extracting water from fogs should be investigated in areas where applying this method is considered. The factors affecting the volume of collected water are (UNEP, 2005):

- *Frequency of fog occurrence:* The frequency of occurrence is a function of atmospheric pressure and circulation, water temperature and the presence of thermal inversions
- *Fog water content:* Fog water content is a function of altitude, seasons and terrain features
- *Design of a fog water collection system:* The design of a system is a function of wind velocity and direction, topographic conditions and the materials used in the construction of the fog collector.

## Assessing the practicality of using a fog mesh in a mine

Air will penetrate a mesh set up perpendicular to the airflow direction, and water is captured on the mesh wires. The optimal mesh size is most probably such that as much water as possible is collected but with the resistance of the mesh such that it does not cause air rerouting. The material characteristics of the mesh are essential as they define the water collecting efficiency and capacity of the mesh. The efficiency of fog mesh will also depend on the size of the fog droplets and on the air velocity. In this study four different materials were examined to compare the behavior of the materials and fog as well as their effects on each other.

As the fog droplets are captured, the condensation nuclei as well as other impurities get caught by the mesh along with the water. Consequently, the system not only dehumidifies the air but also collects and removes particles acting as condensation nuclei from the airflow. Decreasing the number of particles in the air reduces further fog formation, and collecting particles also purifies the air. The fog mesh actually addresses both prerequisites for fog formation.

In a mine a solid wall will cause humid air to move to another route and take the fog with it. Also, a solid wall prohibits the driving of vehicles through the tunnel and is thus not sensible in a mine. This is why the water collecting mesh should be designed as a drive-through structure, especially if built in the decline.

Because the thickness of fog varies, fog removal may not be needed continuously, especially in mines where fogging is only a seasonal problem, and fog removal systems should be designed for easy removal. Fog mesh may be designed so that it can be lifted up and attached to the frame when not needed. This will also keep the mesh fabric out of harm's way in case of higher-speed traffic associated with better climatic conditions.

The requirements for fog collector meshes outdoors are presented as a part of the United Nations Environment Program's fog water collection information. If these prerequisites are compared to the conditions found underground, it is easy to notice the similarities and thus the potential of an underground fog mesh system. These prerequisites are:

- frequency of fog occurrence,
- fog water content,
- wind direction,
- stability of airflow and
- topography.

Usually, fog tends to stay in the same areas of the mine for long periods, even for months. The water content of the air is high in an underground mine because of high particle concentration. The air moves to the same direction in the decline at all times, so wind direction is stable. Air velocity and temperature are also nearly constant in most cases. Being upslope, the topography in a ramp is suitable.

The advantages of the fog mesh are its passive nature and low costs. The system does not require any energy input for operation. It is simple to design and can be constructed quickly and easily. The robust and simple design of the system makes the operational duration long. Maintenance needs are also low because problems that would occur outdoors, such as birds and insects getting caught to the net, are eliminated underground.

## Field tests

**Fogging at the Pyhäsalmi Mine.** Field tests were carried out at the Pyhäsalmi Mine, which is a 1,445-m- (4,740-ft-) deep zinc-copper mine in Finland. The ventilation system of the Pyhäsalmi Mine is discussed thoroughly by Pulkkinen and Martikainen (2004).

Fogging is observed mainly in the decline but also in some old, abandoned levels where fog occurs in some places almost year around. As the velocity of air, relative humidity and temperature vary along the ramp, fog thickness and fog front locations change accordingly. These variations may be caused by water seepage, pumping stations, level connections and shaft connections, which all affect the parameters controlling fog formation. Changes in fog thickness, fog front lengths, fog clouds and locations of foggy areas also depend on factors like the climatic conditions on the surface, diesel equipment usage in the mine, and the length of a working sequence at a time.

In the Pyhäsalmi Mine, fog in the ramp is not considered a serious problem because the ramp is not used as a haulage road. Only a supply truck uses the ramp regularly, and it has no strict schedule. Other vehicles that use the ramp occasionally are mainly for maintenance, inspection and surveying purposes (Martikainen, 2005). This was, in fact, one of the reasons for choosing the mine as a test site. Light traffic does not hinder the measurements or stop frame building often.

Previous fog removal efforts in the Pyhäsalmi mine included increasing air velocity in the ramp by rerouting and prohibiting water flow from entering the ramp. The possibility of air heating has also been discussed.

**Test site and testing procedure.** The chosen test site was in a ramp a bit below Level +600, where fog is usually thick. The tunnel dimensions in the test site are about 5.5 by 4.5 m.

There is an old ventilation wall frame at the test site. This rectangular opening was used for installing the mesh perpendicular to the airflow. The area to be covered with a mesh was approximately 20 $m^2$ (215 sq ft). The meshes were affixed to the upper edge of the frame.

In this case construction was easy, as the old ventilation wall frame was modified for this purpose. Modifications amounted simply to wall frame repair and adding wood planks for mesh attachment. Tested meshes consisted of slices of a mesh fabric, wood planks on the top of the mesh and a heavy electrical cable used as a weight on the bottom of the mesh. This was used to prevent mesh movement with the airflow. The frame and mesh structure is shown in Fig. 1.

All tests were performed in the decline downstream and upstream of the mesh frame. This was done to check the changes of air velocity, humidity and temperature over the fog mesh to evaluate the effects of the mesh. The distance from the mesh was 25 m (82 ft) in both directions, so the measurements were performed 50 m (164 ft) apart (Fig. 2).

All tests were carried out for about 30 minutes after erecting each fog mesh material. This gave time for the airflow to stabilize and find new routes in case there were resistance problems. This also allowed time to check the water collecting ability of the tested mesh fabric and whether or not the water fell down the net. Each test took 10 minutes to perform in one location.

The measurements were performed with every mesh material as well as with only the frame for comparison purposes. This way, changes in airway resistance and air rerouting were easily observed. The comparison measurements are denoted later as the baseline.

**Fog mesh materials.** Four mesh materials were tested. All mesh materials are shown in Figs. 3 through 6. The first material is a mosquito net made of thin metallic wires coated with plastic. The holes of the mesh are rectangular and the mesh size is 1.4 mm. The second material is also a mosquito net but is thinner and made completely of plastic with a mesh size of about 1.0 mm. The third net is designed to protect bushes and trees from the sun or cold. This mesh is made of woven plastic bands. These bands are 1 mm wide. The mesh consists of triangular holes with a height of 7 mm and the length of the shortest side of 3 mm. The fourth material is a 10-mm-thick filter fabric for air cleaning. The filtering efficiency or the grade of the fabric is G3.

**Measurements and measurement devices.** The measurements taken were air velocity, relative humidity, dew point, temperature and dust content. Air velocity and temperature measurements were performed with a hot wire anemometer, Model Kimo VT200. The detection range of the anemometer is air velocities of from zero to 40 m/s (130 fps) and temperatures from -100° to 400°C (-150° to 750°F). The precision of air velocity measurements is 0.01 m/s (0.03 fps), and the precision of temperature measurements is 0.1°C. The accuracy of air velocity value is ±3% ±0.03 m/s of the reading and the accuracy of the temperature value is ±2% ±0.1°C of the reading.

Humidity measurements and verification of air temperature measurements were done with an Ebro TFH100 hygrometer, which measures relative humidity from zero to 100% and temperatures from -10° to 80°C (14° to 176°F). The resolution of the instrument for relative humidity is ±0.1%. The accuracy of the relative humidity, temperature and dew point temperature measurements are ±2% of the readings.

An aerosol meter, DustTrak TSI 8520, with a maximum particle size range of 0.1 to 10 µm was used for dust content measurements. The aerosol meter has a measuring range of 0.001 to 100 mg/m$^3$ and a resolution of 1% of the measuring range.

**Costs of the fog mesh.** As the old ventilation wall frame was used, the costs of the installation were low. The costs of wood planks, wire and nails are very low and considered negligible. About 5 m (16 ft) of electric cable was attached to the mesh fabric. The electric cable was a remnant from an electrical assembly. Cost of the cable is also minimal, estimated to be less than $20. In a mine there is typically a lot of leftover materials, that could be used for fog mesh and frame installation.

The costs of fog mesh materials varied from $30 ($1.2 /m$^2$) to $1,200 ($48/m$^2$). The plant cover net was the cheapest and the grey mosquito net was the most expensive. The price of the white mosquito net was $180 and the price of filter fabric was about $200. All costs are given for the total of 25 m$^2$ (270 sq ft) of mesh material.

Therefore, the costs of the fog mesh system depend mainly on the mesh material. The variation of the prices was noticeable. However, the investment costs are still very low in comparison to other fog removal devices and systems. As the system does not use any energy, there are no operational costs.

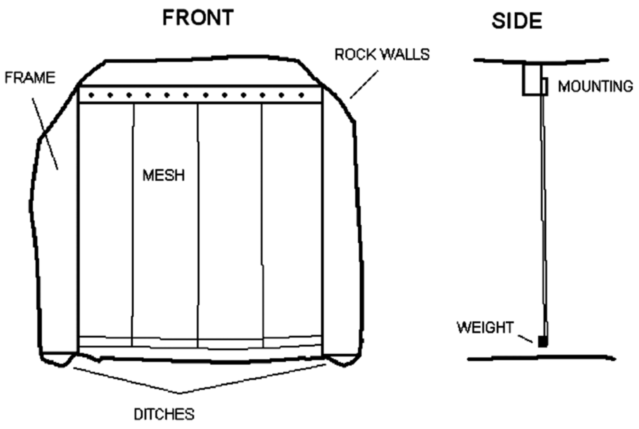


**Figure 1** — Fog mesh installation.

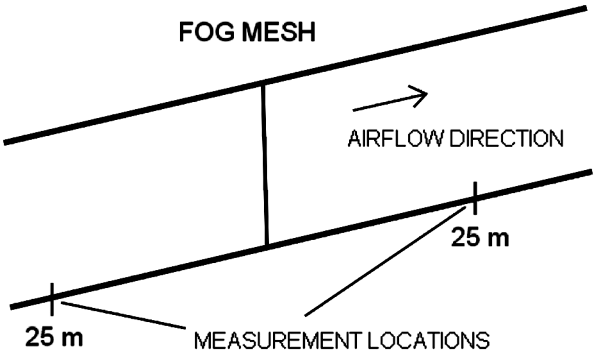


**Figure 2** — Measurement locations.

## Results

**Condition evaluation.** As expected, the results varied quite a lot depending on the mesh fabric material. Unfortunately, the fog situation also varied a lot during the measurements. Fog moved in clouds as pulses through the test site. Sometimes there was almost no fog at all, when at best fog thickness was considered moderate. At no time during the tests was fog observed to be thick. Another problem was the inconsistent nature of the airflow at the test site. As fogginess varies, it is obvious that humidity varies as well.

These problems resulted from the opening and usage of a new waste pass during the tests. Fortunately the changes in temperature and air velocity were minimal as the waste pass is quite far away, about 600 m (1,970 ft) deeper than the testing site. Nevertheless, all this was taken into account during testing as well as in result evaluation.

**Measurement results evaluation.** The measurements without a fog mesh gave a baseline required for comparison. The particle concentration as well as the relative humidity were slightly higher downstream of the frame. This shows that in the test site fog may start forming or observed fog gets slightly thicker. The temperature slightly decreases downstream, as was

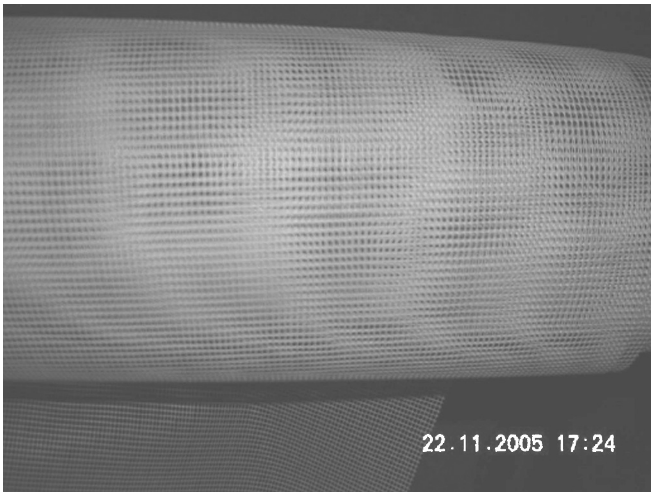


**Figure 3** — Grey mosquito net.

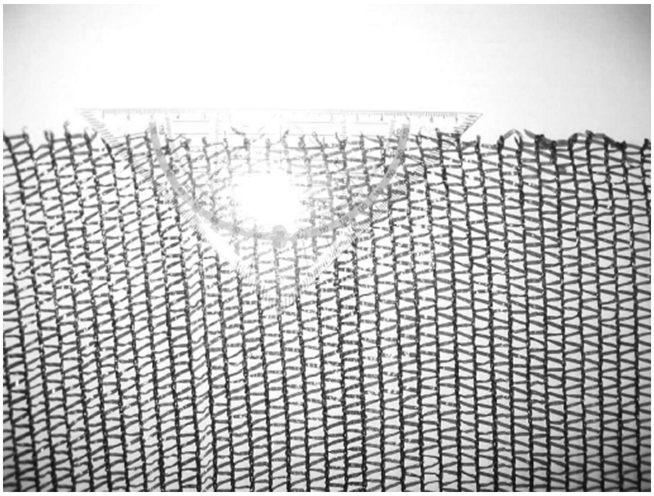

**Figure 5** — Plant cover net.

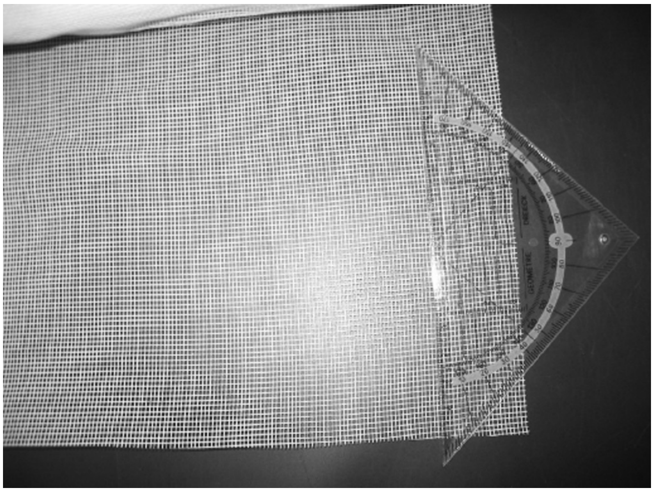

**Figure 4** — White mosquito net.

**Figure 6** — Filter fabric, G3.

expected. The biggest difference was in the air velocity value, which results from a smaller cross-sectional area of the tunnel downstream of the mesh frame.

The first material, the plastic covered metallic mosquito net, was found to be extremely wet, even if there was not much fog at the test site during the time of the measurements. Thin water streams were found running down the net. During the measurements with this fog mesh, measured air velocities were slightly higher than the baseline measurements. This air velocity pulse carried a lot of particles with it. Over the mesh air velocity decreased only slightly. The decrease in relative humidity was noticeable. Particle concentration also decreased considerably.

With the second material, the thin plastic mosquito net, all measured values were slightly decreased in comparison with baseline readings. At the time of the measurements there was some fog, but not much. The mesh fabric was relatively dry after the 30-minute waiting period and was still dry after the measurements.

The woven plastic band net was wet after the waiting period and lowered the relative humidity a lot more than the white, thin plastic mosquito net. The temperature did not change over the mesh, but all the other values decreased somewhat.

The filter fabric was the only one of the materials considered to cause air rerouting, as the air velocity values dropped considerably. The decrease downstream of the mesh was as much as 50%. Also, most of the particles were probably carried through an alternative route. Temperature stayed stable over the mesh. The most remarkable change in relative humidity was achieved with this material. The fabric was completely wet already before the end of the 30-minute waiting period. Water did not, however, fall or run down but seemed to get collected in the fabric, making it extremely heavy and difficult to operate.

All tested fog meshes worked to decrease humidity and particle concentration as expected and planned. Temperatures either stayed the same over the mesh or changed only slightly. Measurement results are shown in Table 1.

The first tested material, the gray mosquito net, was considered best because of the 2% decrease in the relative humidity over the mesh, which gave more than 2.5% decrease in comparison with the baseline, a situation without any fog removal device. Also the decrease of the particle value was as high as 0.25 $mg/m^3$.

**Table 1** — Measurement results.

| Mesh tested/location | Particles, mg/m$^3$ | Air velocity, m/s | Temp., ˚C | Relative humidity, % | Dew point, ˚C | Notes |
|---|---|---|---|---|---|---|
| **Gray mosquito net, plastic covered metal:** | | | | | | |
| Upstream | 1.15 | 1.2 | 18.4 | 92.2 | 17.5 | Light fog, extremely |
| Downstream | 0.9 | 1.0 | 18.9 | 90.2 | 17.6 | wet mesh |
| **Filter fabric, G3:** | | | | | | |
| Upstream | 0.31 | 0.7 | 19.5 | 88.5 | 17.7 | Almost no fog, mesh |
| Downstream | 0.24 | 0.5 | 19.5 | 85.5 | 17.5 | wet throughout |
| **White mosquito net, plastic:** | | | | | | |
| Upstream | 0.61 | 0.9 | 19.0 | 91.8 | 17.9 | Light fog, almost |
| Downstream | 0.54 | 0.85 | 18.8 | 91.4 | 17.6 | dry mesh |
| **Green plant cover net, woven plastic band, polyethylene:** | | | | | | |
| Upstream | 0.71 | 1.0 | 18.8 | 92 | 17.7 | Light fog, wet mesh |
| Downstream | 0.63 | 0.8 | 18.8 | 90.5 | 17.5 | |
| **Baseline – without mesh:** | | | | | | |
| Upstream | 0.83 | 0.85 | 18.8 | 92.3 | 17.9 | Light fog |
| Downstream | 0.93 | 1.0 | 18.6 | 92.9 | 17.8 | |

The different behaviors of the two mosquito nets were observed and reasons for this are considered to be the slight difference of mesh size, but even more importantly the materials themselves. Plastic mesh did not work as well as the plastic-covered metal mesh. As metals conduct heat well, the small temperature changes may have affected the mesh by improving its water collecting efficiency.

Even if the effectiveness of the filter fabric in decreasing the relative humidity was high, giving a 3% decrease, the resistance was also high, altering part of the airflow to other routes. The water gathering and bearing behavior of the material was also problematic already during testing.

**Design considerations.** During testing, three vehicles passed the fog mesh installation. Two of the vehicles drove through the white mosquito net, one through the plant cover net. The speed of all the vehicles was very low, close to a walking speed. One of the vehicles drove up the ramp and two drove downward. Two of these had no problems with the fog mesh. The mesh slid over the vehicles smoothly. This was promising.

However, the long antenna of the last vehicle, which was driving down the ramp against the airflow, got caught on a wire that was used to attach the weight to the frame. The antenna was detached manually from the wire, but this suggests that attention should be paid towards design issues concerning how the weight is attached to the mesh. An improved attachment arrangement of the weight is expected to solve this problem.

Also, other aspects of the design will be considered in future testing, especially if an effective mesh material that justifies developing the system further is found.

## Further studies

As the results of the field tests were promising, further studies are already under way. How to improve the water collection efficiency of the mesh is the most important consideration. Optimal material characteristics of the mesh may be the answer to this question. Tests in another mine with different humidity, temperature and particle concentration values and thus different fog characteristics may be enlightening. Another question is the effect of multiple-mesh systems. It would be interesting to know if it is possible to lower humidity and particle concentration values with about the same degree over every single mesh in a multiple-mesh system or will the effect weaken when humidity and particle concentration values are decreased.

On the other hand, if multiple-mesh systems are needed for fog removal, the resistance of the system may rise so high that air redirects to alternate routes, which may prove to be impractical. Also, the investment costs are multiplied in a multiple mesh system. If optimal material characteristics are found with low cost meshes, then optimizing other aspects is also worthwhile.

A water collection system may be practical in some cases. At least open ditches to which water can be drained decreases wet surface area near the mesh and thus keeps fog from forming. This could also be studied further.

## Conclusions

Even if the conditions for testing were not optimal, the results were very promising. The mesh materials reacted differently, but positively for fog removal purposes. Further positive results are expected in future testing.

One problem, air rerouting, was expected, but fortunately it was only realized with one of the tested materials, namely, the filter fabric. As this material was impractical also because of its water-bearing behavior, it can be ruled out as a fog removal mesh underground.

All four of the tested materials decreased humidity and particle concentration. The effect on the air velocity was only a slight decrease in most cases, so the method can be regarded feasible also in this aspect. It can be concluded that the theory has proven to work well in practice. The question of whether or not the decrease in relative humidity and particle concentration is enough for effective fog removal still remains to be discovered in further studies.

## Acknowledgements
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