Mine Planning and Equipment Selection 1995, Singhal et al. (eds) © *1995 Balkema, Rotterdam. ISBN 90 5410 569 0*

Estimation of the air quality index in the case of operation of numerous diesel-powered units in Greek underground bauxite mines

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ABSTRACT : Availing of the indisputable advantages of diesel-powered equipment, the mining industry concentrates its efforts towards the minimization of undesirable effects, the most significant of which is the imperfect fuel combustion.

The continuous monitoring of the underground mine ventilation network, especially in the cases of high concentration of toxic gases, requires the installation of numerous sensors. Thus, multiple point indications secure the measured values. The decrease of the necessary number of sensory devices and the determination of their optimal installation sites, were the main aims of the research. As a result, a new methodology for achieving reliable value estimations between the existing point indications was developed.

The estimation of the Air Quality Index (AQI) in a given area where different types of equipment are in operation, is rather difficult. Besides the measurement of CO concentration, both its proportional distribution - on the basis of the quantity emitted by every different machine - and the estimation of the concentration of the remaining pollutants, are required.

A prototype method, based on the introduced term of the "mean time-weighted Air Quality Index" ($\overline{AQI}_{At}$) and on the measurement of CO and particulate matter (PM) concentrations, was developed. Thus, the estimation of the atmosphere quality, in areas where numerous diesel-powered equipment units are in operation, becomes easier.

1. INTRODUCTION - UNDERGROUND MINE ATMOSPHERE QUALITY CONTROL

A miner working underground where diesel equipment is used, is exposed to a wide variety of exhaust pollutants. These include carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, sulphur dioxide, hundreds of different hydrocarbons (HC's) and diesel particulate matter (DPM). The US National Institute of Occupational Safety and Health (NIOSH) and the US International Agency for Research on Cancer (IARC) have respectively declared diesel exhaust to be "potentially" or "probably" carcinogenic (Watts, 1987).

DPM is a complex mixture of chemical compounds, composed of nonvolatile carbon, hundreds of thousands of different absorbed or condensed HC's, sulphates and trace quantities of metallic compounds. DPM is of special concern because it is almost entirely respirable, with 90 pct of the particles, by mass, having an equivalent aerodynamic diameter of less than 1.0 μm. This means that the particles can penetrate to the deepest regions of the lungs and, if retained, cause or contribute to the development of lung disease. Of greater concern is the ability of DPM to absorb other chemical substances, such as potentially mutagenic or carcinogenic polynuclear aromatic hydrocarbons (PAH's), gases (such as sulphur dioxide and nitrogen dioxide), as well as sulphur and nitric acids. DPM carries these substances into the lungs, from where they may be removed and transported by body fluids to other organs, where they may cause damage.

The exhaust pollutants emitted from the combustion process of diesel engines represent a principal concern over the use of the equipment in underground mines. Because of increasing mechanization, underground mining has become less dependent on large, concentrated work forces. Many operations have a few persons working in many different and scattered sections, which make the mobility of diesel-powered equipment very attractive in mine feasibility and design studies. The versatility of the equipment is also an advantage since a single piece of equipment can be modified to perform the many different functions required of transportation of both workers and supplies.

The issue of proper control of diesel exhaust emissions is complex. The quantity, chemical composition and physical property of exhaust emissions change during normal engine operating conditions. Emissions are affected by the type of engine, duty cycle, fuel quality, maintenance, intake ambient air conditions, operator habits and emission controls.

The continuous monitoring of the underground mine ventilation network, especially in the cases of high concentration of toxic gases, requires the installation of numerous sensors. Thus, multiple point indications secure the measured values. The role of a similar system, as an organic part of a mechanized underground mine, requires a high expenditure in equipment purchase and man-hours. The great number and variety of the sensors leads to a more complicated system which is prone to frequent failure phenomena, thus, frequent maintenance work may be required and low reliability value is obtained.

The decrease in the necessary number of sensory devices and the determination of their optimal installation sites, are of great importance. A methodology for achieving reliable value estimations between the existing point indications was developed.

Towards the above aim, an automatic air quality monitoring system has been designed and developed, during a research project, based on the structure of an IBM, PC/AT compatible computer adapted to the requirements of a Greek underground bauxite mine, owned by the "BAUXITE PARNASSE Mining Co." (Economopoulos et al, 1992) . The system was installed in the underground bauxite mine "ANO VARIANI -ADITS 715-740", in order to confirm the new methodology. The necessary experimental tests were executed for determining the application field of the system and evaluating the main parameters which may dramatically affect its performance.

The main bauxite deposits in Greece expand within the geosyncline of Parnassos-Giona-Helicon-Oiti mountains, the main axis of which has a northwest-southeast orientation. The deposits belong mainly to the uppermost third bauxite horizon, which is of diasporic type and is surrounded by fully stratified microcrystalline limestones. The hangingwall of the deposits consists of dark-coloured, rudistic, bituminous limestones of the Turonian-Senonian period. The footwall of the deposits consists of lower Cretaceous white limestones which are always establishing a characteristic angular unconformity with the hangingwall. Extraction of bauxite is usually performed by mechanized room and pillar mining method.

The AQI constitutes the most remarkable qualitative criterion of the underground hard-rock mine atmospheres and is the only one known to have been developed that incorporates the additive effects of the pollutants when found in combination. It was defined in 1978, by Ian W. French and Associates, Ontario, Canada, and involves the measurement of the exhaust pollutants, CO, NO, SO_2, NO_2 and respirable combustible dust (RCD), on a time-weighted average (TWA) basis. This RCD term is an estimate of diesel particulate (carbon based particles) in hard rock mines that do not contain carbon in the host rock. The values of the pollutants measured underground are used to calculate a numerical value for the AQI using the following formula :

$$AQI = \frac{CO}{50} + \frac{NO}{25} + \frac{RCD}{2} + 1.5\left(\frac{SO_2}{5} + \frac{RCD}{2}\right) + 1.2\left(\frac{NO_2}{5} + \frac{RCD}{2}\right) \qquad (1)$$

where the concentration of RCD is expressed in milligrams per cubic meter and all other concentrations are expressed in parts per million.

French and Associates indicate that an AQI value between 3.0 and 4.0 poses a moderate threat to health, while, a value in excess of 4.0 indicates a health hazard level and the need for increased ventilation or pollutant source controls to bring the value back to less than 3.0.

In 1984, this AQI was modified into two-part index to resolve criticisms of some health researchers. It is now suggested that two independent equations, one for the gases and one for the respirable dust and SO_2 and NO_2 components must be used as follows:

$$AQI_{(gas)} = \frac{CO}{50} + \frac{NO}{25} + \frac{NO_2}{5} \qquad (2)$$

$$AQI_{(particulate)} = 3\cdot\frac{RCD}{2} + \frac{SO_2}{5} + \frac{NO_2}{5} \qquad (3)$$

It is recommended that the AQI(gas) and the AQI(particulate) values should not exceed 1.0 or 2.0, respectively, and no individual component should exceed its threshold limit value (TLV).

2. RELATIONS BETWEEN THE DIESEL EXHAUST POLLUTANTS

It is not practical to measure all the compounds of diesel exhaust in the underground mine environment and therefore, a selective monitoring methodology is required that will accurately assess the overall air quality when diesel units are used. The US Bureau of Mines has been developing a monitoring methodology that requires only the measurements of CO_2 to assess the mine atmosphere. Once the relationship between the other pollutants and CO_2 has been established for a specific equipment and mine conditions, CO_2 becomes a surrogate for the other pollutants. The monitoring methodology makes use of the AQI, which combines the individual and synergetic health effects of the pollutants, to provide a relatively numerical value to assess air quality (Daniel, 1984).

A validation of the aforementioned methodology of CO_2 in multi-diesel machine operation, typical of small underground mines, has been announced by other researchers (Gangal et al, 1991).

A linear relationship of CO_2 concentration with other diesel emitted pollutants was indicated by the results of simultaneous real-time monitoring of CO_2 with CO, NO, NO_2, SO_2 and RCD in several small underground mines, where 1, 2 or 3 diesel units were in operation. Regression analysis shows that, at the 1 percent level of significance, there is a strong linear relationship of these diesel pollutants with CO_2.

Measurements in diluted and non-diluted Diesel emissions carried out by the authors in underground bauxite mines showed similar results for the gaseous pollutants. Generally, it can be assumed that the ratios of CO concentrations to the respective concentrations of the remaining gaseous pollutants, such as SO_2, NO_x and CO_2 were changed within a standard range and were characterized by relatively stable mean values, within a confidence interval, for a specific equipment and mine environment. Thus, the estimation of the concentrations of the main emitted gaseous pollutants nearby a diesel-powered unit can be possible, when the CO concentration value is given.

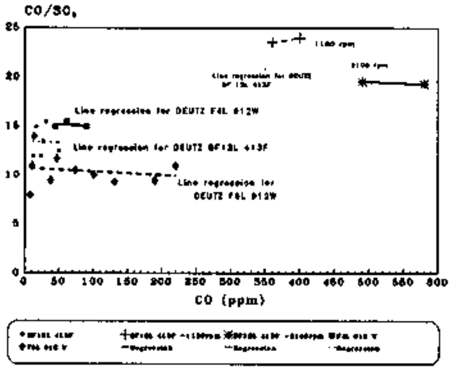

Figure 1. Values of the ratio CO/SO_2 in conjuction with the CO concentration.

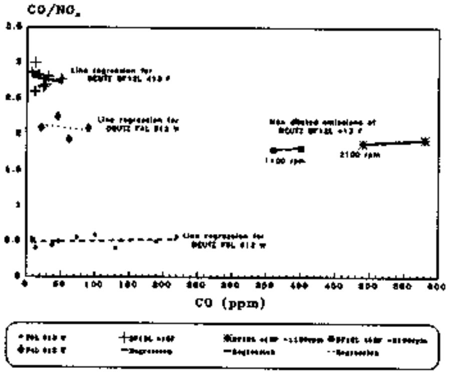

Figure 2. Values of the ratios CO/NO_x in conjuction with the CO concentration.

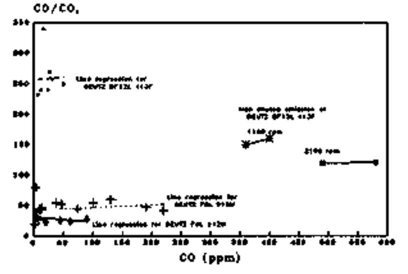

Figure 3. Values of the ratios CO/CO_2 in conjuction with the CO concentration.

Figures 1, 2 and 3 show these stable mean values of the ratios CO/SO_2, CO/NO_x and CO/CO_2 for the specific equipment that was in operation in the bauxite mines (LHD GHH units, drilling jumbos SECOMA and roofbolting jumbos SECOMA, powered by DEUTZ engines of type BF12L 413F, F6L 912W and F4L 912W, respectively).

The use of mathematical analysis based on the error theory of statistics can be employed in order to provid an estimation of AQI with respect to the CO and PM concentrations in the operation area of the occasionally existing equipment.

Considering that λ_{NO}, λ_{NO2}, λ_{SO2} and $\sigma_{\lambda NO}$, $\sigma_{\lambda NO2}$, $\sigma_{\lambda SO2}$ represent the values and the typical standard deviation of the ratios CO/NO, CO/NO_2 and CO/SO_2, respectively, in the 5 percent level of significance, the AQI can be presented as follows :

$$AQI_{(g)}=\frac{[CO]}{50}+\frac{[CO]}{25\cdot\lambda_{NO}}+\frac{[CO]}{5\cdot\lambda_{NO_2}}\pm\frac{[CO]}{5}\cdot\sqrt{\left(\frac{\sigma_{\lambda_{NO}}}{5\cdot\lambda_{NO}^2}\right)^2+\left(\frac{\sigma_{\lambda_{NO_2}}}{\lambda_{NO_2}^2}\right)^2} \qquad (4)$$

$$AQI_{(p)}=\frac{3}{2}RCD+\frac{[CO]}{5\cdot\lambda_{SO_2}}+\frac{[CO]}{5\cdot\lambda_{NO_2}}\pm\frac{[CO]}{5}\sqrt{\left(\frac{\sigma_{\lambda_{SO_2}}}{\lambda_{SO_2}^2}\right)^2+\left(\frac{\sigma_{\lambda_{NO_2}}}{\lambda_{NO_2}^2}\right)^2} \qquad (5)$$

Furthermore, the concentration of every emitted pollutant must not exceed its TLV value, thus

$[CO] < 50$ ppm,

$$[NO] < 25\ ppm \Rightarrow \frac{[CO]}{\lambda_{NO}\pm\sigma_{\lambda_{NO}}} < 25ppm \Rightarrow [CO] < 25\cdot(\lambda_{NO}\pm\sigma_{\lambda_{NO}})\ ppm$$

$$[NO_2] < 5\ ppm \Rightarrow \frac{[CO]}{\lambda_{NO_2}\pm\sigma_{\lambda_{NO_2}}} < 5ppm \Rightarrow [CO] < 5\cdot(\lambda_{NO_2}\pm\sigma_{\lambda_{NO_2}})\ ppm$$

$[RCD] < 2\ mg/m^3$
HC's < 5 ppm

Although the estimation of AQI is based on the measurement of two main pollutants, it is rather different when compared to similar estimation methods, based on the measurement of CO_2. They were not absolutely verified during the executed tests of this research. The observed difference is due to the highly changeable concentration of the emitted DPM which depends on a variety of factors and does not give a constant value of the CO/DPM ratio.

Moreover, absorbed soluble organic fractions (mainly aromatic hydrocarbons) have been observed in the solid part of DPM. They generally cause serious damages to the health of the exposed mineworkers and may be considered as probable causes of cancer deceases. The diesel particulates are predominantly less than 1 μm in aerodynamic diameter, hence, represent the most severe health hazard of the combustion products since they can be inhaled and retained in the lungs. The estimation of AQI is recommended to be based on the direct measurment of PM.

Establishing the gaseous pollutants characteristic curves involves specialized and expensive instrumentation, as well as trained personnel to collect and analyze the data. Usually it can not be done by present mining staffs, but must be accomplished by consultants or service organisations.

Figure 4 presents the slope of the characteristic curves of the CO/NO ratios, in the cases of the small underground mines #1, #2 and #3 (mentioned by Gangal's et al research work) and the occasionally operated diesel-powered units in the Greek underground bauxite mines. It is obvious that the ratio value (slope) is different in every case and for this reason, the methodology for the assess of air quality must be up-grated in order to include the operation of numerous diesel units.

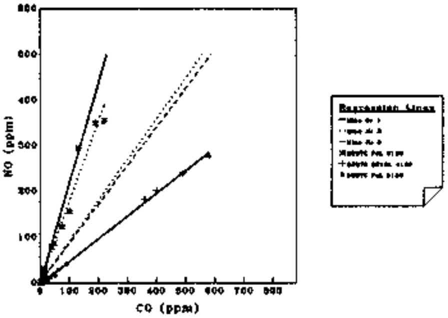

Figure 4. Characteristic curves of the CO/NO ratio in various cases.

Changing engine conditions due to wear, maladjustment and improper maintenance will alter the slope of the pollutant characteristic curves so that actual engine gaseous pollutants correlations will no longer be representative by the curves established by the original operating conditions. A simple tailpipe exhaust analysis method is necessary to indicate changes in engine conditions so that the engine may be restored to its operating condition under which the characteristic curves were established.

3. INTRODUCTION OF THE TERM "MEAN TIME - WEIGHTED AIR QUALITY INDEX" $AQI_{\Delta t}$

The estimation of AQI in a given area where different types of equipment are in operation, is rather difficult. Besides the measurement of CO concentration, both its proportional distribution - on the basis of the quantity emitted by every different machine - and the estimation of the concentration of the remaining pollutants, are required.

The distribution of the CO measured concentration depends on the mean time-weighted emitted quantity of CO and the emitting (operation) time of each different machine. The parameters affecting the estimation of the emitted CO of each machine is the emitted quantity, the distance between the emission point and the measuring point as well as the dilution model of CO. The dilution model of pollutants depends on the air flow and the network of the underground mine. It constitutes the most important parameter for the estimation of the AQI in an area where numerous Diesel equipment are in operation.

For determining the emitted pollutants' dilution models of the specific mine environment and underground layout, a research program was executed in the Greek bauxite mines, with the following main results :

- The different dilution models of the exhaust pollutants of each diesel-powered unit remain inactive at a distance greater than 8-10m from the emission point, in the given underground bauxite mine network, where the usual exploitation method is room and pillar mining.
- Beyond the distance of 8-10 meters it is considered that the dilution of the exhaust pollutants is generally determined by the ratio of pollutants to clean air supply. In the specific parts of the underground network, where the supply of pollutants and clear air remains constant, the concentration of pollutants may be considered as stable.
- When analytical determination of the distribution models of pollutants, at a distance shorter than 10 meters from their emitting point, is desired, both the dispersion of PM and the concentration of the emitted gaseous pollutants can be accurately calculated by using the appropriate recommended formula.

In general, it can be assumed that, if in a given time interval Δt and in the vicinity of a point X, arrive $Q_1, Q_2, \dots, Q_v$ air quantities from discrete positions, where numerous diesel-powered units $M_1, M_2, \dots, M_v$ are in operation (fig. 5) and $Q_{v+1}, Q_{v+2}, \dots, Q_\lambda$ air quantities aggravated by diesel pollutants concentrations (due to recirculation), then the "mean time-weighted Air Quality Index" can be determined by using the following type (Kontothanassis, 1994):

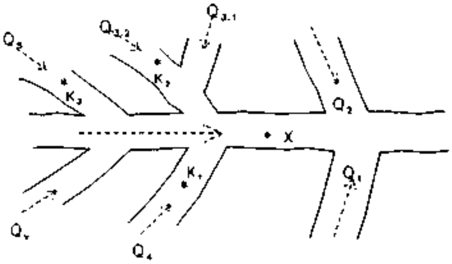

Figure 5. Schematic diagram of a typical mine layout.

$$\overline{AQI_{\Delta t}} = \frac{\sum_{i=1}^{v}(UOF_i \cdot Q_{F_{oi}} \cdot AQI_{oi}) + \sum_{j=v+1}^{\lambda}(FO_j \cdot AQI_{oj} \cdot Qj)}{\sum_{i=1}^{v} Q_i + \sum_{j=v+1}^{\lambda} Q_j} \qquad (6)$$

where,

AQI_{Ui} = the mean value, in the time Δt, of the AQI for the non-diluted emission of the unit i.
Q_{PUi} = the mean value, in the time Δt, of the unit i emitted quantities (m^3/s).
AQI_{Qj} = the AQI value of the air quantity j.
Q_i, Q_j = the value of the air quantity i, j (m^3/s).
UOF_i = the unit i operating factor during the time Δt. It corresponds to a fraction of the time Δt where the unit i was in operation ($0 < UOF_i < 1$).
FO_j = the air quantity Q_j factor. It corresponds to a fraction of the time Δt where the air quantity Q_j was existed.

In order to reliably estimate the $\overline{AQI}_{\Delta t}$ in a given area it is necessary to nullify the term :

$$\sum_{j=\nu+1}^{\lambda} (FO_j \cdot AQI_{Q_j} \cdot Q_j) \qquad (7)$$

which can be accomplished by choosing the proper measurement positions, where no recirculation of air is observed. The nullification of the term (7) is the best criterion for guidelining the measurement points for the installation of the CO and PM sensors, in the cases where a real time atmosphere monitoring system is necessary.

A sharing factor of each operated unit i (SF_{COi}) in the vicinity of the point X (on the basis of the proportional distribution of the emitted quantities by each machine) is required to be established, after each measurement of the CO and PM concentrations.

These factors are generally satisfying the following formula :

$$\sum_{i=1}^{\nu} (SF_{CO_i}) = 1 \qquad (8)$$

The reliable estimation of the gaseous emitted pollutant concentrations NO, NO_2 and SO_2 from each operating unit i, is accomplished by the following equations :

$$[NO] = \sum_{i=1}^{\nu} \frac{SF_{CO_i} \cdot [CO]}{\lambda_{NO_i}} \;,\quad [NO_2] = \sum_{i=1}^{\nu} \frac{SF_{CO_i} \cdot [CO]}{\lambda_{NO_{2i}}} \;,\quad [SO_2] = \sum_{i=1}^{\nu} \frac{SF_{CO_i} \cdot [CO]}{\lambda_{SO_{2i}}} \qquad (9)$$

Using the equations (9), the equation (6) is transformed as :

$$AQI_{(g)} = \frac{[CO]}{50} + \sum_{i=1}^{\nu} \frac{SF_{CO_i} \cdot [CO]}{25 \cdot \lambda_{NO_i}} + \sum_{i=1}^{\nu} \frac{SF_{CO_i} \cdot [CO]}{5 \cdot \lambda_{NO_{2i}}}$$

with error calculation :

$$\pm\sqrt{\sum_{i=1}^{\nu} \left(\left(-\frac{SF_{CO_i} \cdot [CO]}{25 \cdot \lambda_{NO_i}^2} \right)^2 \cdot \sigma_{\lambda_{NO_i}}^2 \right) + \sum_{i=1}^{\nu} \left(\left(-\frac{SF_{CO_i} \cdot [CO]}{5 \cdot \lambda_{NO_{2i}}^2} \right)^2 \cdot \sigma_{\lambda_{NO_{2i}}}^2 \right)}$$

and

$$AQI_{(p)} = \frac{3}{2} RCD + \sum_{i=1}^{\nu} \frac{SF_{CO_i} \cdot [CO]}{5 \cdot \lambda_{SO_{2i}}} + \sum_{i=1}^{\nu} \frac{SF_{CO_i} \cdot [CO]}{5 \cdot \lambda_{NO_{2i}}}$$

with error calculation :

$$\pm\sqrt{\sum_{i=1}^{\nu} \left(\left(-\frac{SF_{CO_i} \cdot [CO]}{5 \cdot \lambda_{SO_{2i}}^2} \right)^2 \cdot \sigma_{\lambda_{SO_{2i}}}^2 \right) + \sum_{i=1}^{\nu} \left(\left(-\frac{SF_{CO_i} \cdot [CO]}{5 \cdot \lambda_{NO_{2i}}^2} \right)^2 \cdot \sigma_{\lambda_{NO_{2i}}}^2 \right)}$$

The installation of the automatic air quality monitoring system and the provided theoretical background, can lead to a more reliable air quality estimation, either in areas where numerous diesel-powered units are in operation or in positions which are flooded by generally polluted air. By using the appropriate coefficients, both the load cycle and the performed work of each unit as well as the undesired recirculation of aggravated air, are taken into account.

The calculation of the correlation factor between the real values of AQI and the theoretical (estimated) values of $\overline{AQI}_{\Delta t}$ is based on the following data:

- ☐ The acquired measurements of the system.
- ☐ The kind of the work executed by each diesel-powered unit.
- ☐ The exact positions of the units in the exploitation area under research.

The validity of the proposed methodology was satisfactory confirmed, due to the quite high value of the correlation factor ($r > 0.9$).

4. CONCLUSIONS

Figure 6 presents a synopsis of the proposed methodology.

The application of the recommended method improves the capabilities of the system for monitoring the atmosphere quality, as it contributes to the satisfaction of the following principle objectives:

a) Minimization of the necessary number of the sensory devices, mainly those for measuring the diesel emitted pollutants' concentrations. The introduced concept of the mean time-weighted Air Quality Index estimates the atmosphere quality in areas where various units are in operation, by using a system which is based on a minimum number of sensory devices. The necessary cost of development, installation and operation of the system is then significantly reduced.

b) Mathematical determination of optimal installation sites of the sensory devices through the minimization of interferences caused by the recirculation of polluted air quantities.

A technique to assess engine operating conditions by exhaust emission analysis is required since the relationship between the gaseous pollutants are affected due to significant changes in engine operating conditions, duty cycle, altitude etc. Furthermore, the technique must be implemented by the mine workers without the need for laboratory

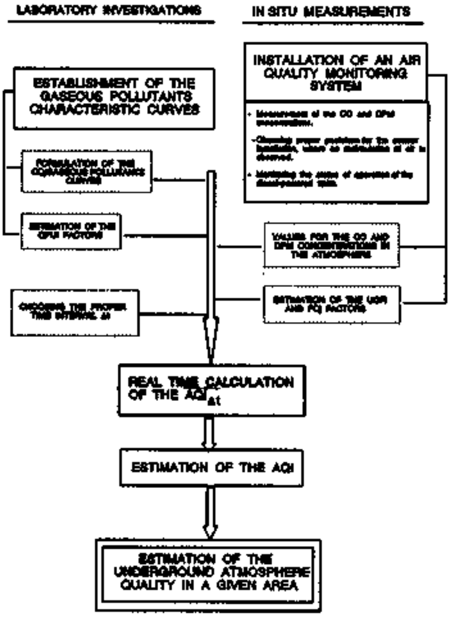

Figure 6. Synopsis of the proposed methodology for the estimation of the AQI.

Instrumentation and trained personnel, in order to be effective for the mining industry.

REFERENCES

Daniel J.H. 1988. Feasibility of CO_2 Monitoring to Assess Air Quality in Mines Using Diesel Equipment, *USBM RI 9160*.

Economopoulos J.N. & P.T. Kontothanassis 1992. Contribution to the study for the development of a data acquisition and control system in mining. *Mining and Metallurgical Annals*, vol. 2, no 3.

Ian W. French and Associates Ltd. 1978. An Annotated Bibliography Relative to the Health Implications of Exposure of Underground Mine Workers to Diesel Exhaust Emissions. *Rep. to the Dep. of Energy*, Mines and Resources, Ottawa, Canada, Dec 11, 350 pp.

Gangal M.K. & E.D. Dainty 1991. CO_2 as an exhaust surrogate in small dieselized mines, *5th US Mine Ventilation Symposium*, West Virginia USA, pp. 280-287.

Kontothanassis, P.T. 1994. *Automatic air quality monitoring in diesel-powered underground mines*. Doctoral Thesis. National Technical University of Athens.

Watts W.F. 1987. Industrial Hygiene Issues Arising From the Use of Diesel Equipment in Underground Mines. *Proceedings: Bureau of Mines Technology Transfer Seminar, USBM IC 9141*.