Mathematical Modelling for Radon Prediction and Ventilation Air Cleaning System Requirements in Underground Mines

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Abstract: As a part of a comprehensive study concerned with control workplace short-lived radon daughter concentration in underground uranium mines to safe levels, a computer program has been developed to calculate ventilation parameters e.g .: local pressures, flow rates and radon daughter concentration levels. The computer program (actually two parts, one for mine ventilation and other for radon daughter levels calculations) has been validated in an actual case study to calculate radon concentration levels, pressure and flow rates required to maintain the acceptable levels of radon concentrations in each point of the mine. The required fan static pressure and the approximate energy consumption were also estimated. The results of the calculations have been evaluated and compared with similar investigation. It was found that the calculated values are in good agreement with the corresponding values obtained using "REDES" standard ventilation modelling software. The developed computer model can be used as an available tool to help in the evaluation of ventilation systems proposed by mining authority, to assist the uranium mining industry in maintaining the health and safety of the workers underground while efficiently achieving economic production targets. It could be used also for regulatory inspection and radiation protection assessments of workers in the underground mining.. Also with using this model, it could be effectively design, asses and manage underground mine ventilation systems. Values of radon decay products concentration in units of working level, pressures drop and flow rates required to reach the acceptable radon concentration relative to the recommended levels, at different extraction points in the mine and fan static pressure could be estimated which are not available using others software.

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Introduction:

The major radiation hazard in a uranium mine originates from the short lived radon – progeny, concentrations of which mainly depend on that of the parent, radon-222, formed within the ore body. Radon enters mine atmosphere by diffusion through the rock surface. The rate of emanation is characterized by the ore grade and porosity of the rock(1,2). Suction effect caused by lowering the atmospheric pressure is another additive factor (3). Although under ground water (4) and broken ore piles also contribute substantially to the radon content of a mine drift, the main supply comes from the continuous diffusion through the ore body. Ventilation plays the most effective role in reducing the airborne radiation levels underground. Knowledge of radon emanation rate is therefore essential for an efficient and economic design of a uranium mine ventilation system. Without proper air distribution and control, even the best contaminant reduction program is inadequate to maintain a healthful atmosphere.

The main objective of a Ventilation Air Cleaning system (VACs) is to provide the quality and quantity of the airflows throughout the mine and to ensure safe and health conditions for the workers to the level specified by the mining regulations. In uranium mines the planning and operation of the ventilation systems have a large impact on production due to the fact that the first engineered step to control radiation contamination is with ventilation. The techniques used to maintain good air quality in uranium mines are based on providing very large volumes of air, maintaining the residence time of the air at a minimum in all working areas, guaranteeing zero recirculation of the air and designing a highly flexible ventilation system.

Good ventilation not only safeguards employee health but also has direct bearing on mine operating cost. The effects of inadequate ventilation are easily masked, and poor ventilation is often the unrecognized cause of high accident frequency, worker dissatisfaction, and production losses. A well planned adequate air distribution system is usually less expensive to install and maintain than a slipshod or makeshift network developed through expediency. The basic criteria for judging the performance of the ventilation system in uranium mines is the level of airborne alpha activity in the working environment. Air volumes and distribution systems suitable for controlling the level of radon daughters usually are adequate for dilution of other air contaminants associated with mine operations [5].

Since radon ^{222}(Rn) is of major concern for occupational health in uranium mines , and the concentration has to be maintained within allowable limits. It is necessary to ensure safe working conditions and occupational health in advance by predicting the expected radon concentrations throughout the underground network and to provide evidence of this in licensing procedure. This can be achieved by numerical modelling of the ventilation network as well as the contaminant transport. Many investigations have intended to present an assessment of radon and radon decay product exposure and to estimate the annual exposure to the workers in the underground mines [6-16]. Also some studies have reported the effectiveness of increased air volumes in diluting radioactive air contaminants [17 and 18]. However in many cases simple air volume increase does not provide a practical solution to persistent high radiation levels, and revised air distribution system must be developed. To improve existing underground ventilation or to plan the ventilation system of a projected mine, a practical computer program (actually two programs, a mine ventilation program and a radon daughter level program) has been written according to the principles outlined in the next sections.

A case study is presented where the values of radon decay products concentration in units of working level for two phosphate mines are calculated and compared with the measured values obtained by others [19]. Also the pressure drop, the air flow rate of the mechanical ventilation required to reach the acceptable radon concentration relative to the recommended levels, fan static pressure and the approximate electrical power consumption for the two underground phosphate mines are investigated and compared with the corresponding calculated values obtained using REDES software[20 and 21]. The formula and computational method used in the mine ventilation and radon computer program are detailed in the following section.

Computational Analysis

1 Mine Ventilation Analysis

1.1 Ventilation networks

A network is a mathematical representation of a real mine ventilation system. Mines consist of many airways interconnected in such a way that it is possible to reduce them to simple series and parallel circuits. The network of airways can, with the use of computers be analyzed to predict airflow quantities and pressures. Fig. (1) represents three possible stages for development of a mine. At first a simple series circuit, expanding when a new area is opened up creating a parallel circuit and finally the connection of the two working areas resulting in a network of airways. The airways in the system are called branches. The branches are interconnected at points called nodes. Each branch is represented by an initial node and a final node. Nodes represent the following:

i- Connections between ducts of the network.

ii- Section change in a duct. iii- Pressure data or pressure unknown.

iv- Height of any point of the network.

v- Source or sink air in any point of the network.

Airflow direction is considered positive if it, goes from initial to final node and vice versa . The flow resistance of each branch depends on its length , section geometry, rugosity, bends, and singularities (elbows, filters, valves, entrance or exit section changes, etc.).

The following data are needed to calculate the branch resistance:

i. Branch length. ii. Branch hydraulic diameter.

iii. Sum of singularities, written as a sum of "equivalent length / hydraulic diameter" of each singularity of the element.

iv. Sum of singularities, written as a sum of dimensionless pressure lost constants of each singularity of the element. V. Inside wall rugosity of the duct.

A ventilation network is very similar to an electrical diagram in which the wires are the branches (underground openings), nodes are the intersections and the calculations that follow are based on Kirchhoff's Laws [22]. The first Kirchhoff's Law is related to the mass flow and states that the mass flow that meets in a junction (node) is zero. The mathematical form of this law is:

$$\sum_{i=1}^{n} M = 0 \qquad (1)$$

where: i, number of branches and M mass of air per unit time that is moved in a branch i, (Kg/s). If we substitute $M = Q\,\rho$, the above formula becomes:

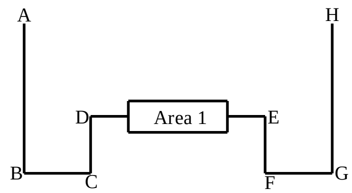
$$\sum_{i=1}^{n} Q_i\,\rho = 0 \qquad (2)$$

where:

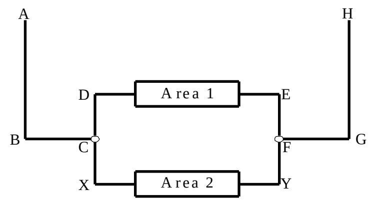
Q_i is the airflow in branch i, (m^3/s),

ρ_i is the air density in branch i, (Kg/m^3) and

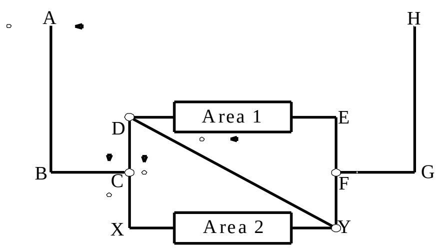
i is the number of branches in the network



Series circuit ABCDEFGH



Parallel circuits CDEF and CXYFwith common junction C and F



Compound or network system

The construction of airway DY presents a different problem consisting of branches, junctions and meshes. Branches (connect junctions) and are ABC, CD, DEF, DY, CXY, YF and FGH (Total 6). A branch is any series of airways and may have different dimensions and must be included at least once in the group of meshes. Junction (two or more branch) C, D, Y, and F (total 4). Meshes (and closed circuit) CXYDC, DYFED, CXYFEDC and ABCXYGHA (total 4).

Fig. (1) : Three possible stages for development a mine (series, parallel and network of airways)

1.2 Ventilation circuits

If the variation in density along each branch is very small, the density effect can be neglected, therefore,

$$\sum_{i=1}^{n} Q_i = 0 \qquad (3)$$

The second Kirchhoff's Law states that the a lgebraic sum of the pressure drops must be zero. In order to apply this law the mesh must be closed so the fans and the pressure differential will move the air. This law can be written as:

$$\Delta u^2/2 + \Delta z\, g + w = \int V\, dP + F \qquad (4)$$

where:
u is the air velocity, (m/s),
z is the elevation above the reference, (m),
w is the work input from fan, (J/Kg),
V is the specific volume, (m³/Kg),
P is the barometric pressure, (Pa) and
F is the work done against friction, (J/Kg)

The terms Δz and $\Delta u^2/2$ will be approaching zero as the mesh is closed. The term $-\int V \times dP$ is the natural ventilating energy per unit mass.

With these two changes, the new form for this law becomes:

$$\sum_{i=1}^{n}(P_i - P_{fi}) - NVP_i = 0$$

(5)

where:
P_i is the frictional pressure drop for each branch, (Pa),
P_{fi} is the the variation in the total pressure across the fan, (Pa) and
NVP is the natural ventilation pressure, (Pa)

1.3 Simple ventilation networks

Equivalent resistances

The equivalent resistance calculation for simple circuits is also similar to electrical circuits and applies to branches connected in series, parallel or combination (auxiliary ventilation).

Series Circuit

The schematic of a series circuit is presented in Figure 6 [23]. The airflow on each branch is the same while the frictional pressure varies.

$$Q = Q_1 = Q_2 = \ldots = Q_b \qquad (6)$$

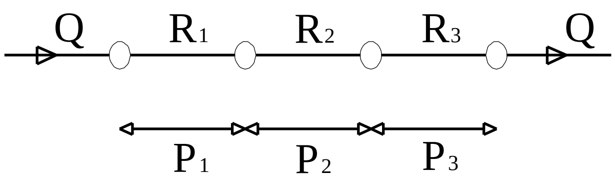


Fig. (2) : Series circuit

The general form for frictional pressure drop on each branch is [23]:

$P_1 = R_1\ Q_1^n \quad P_2 = R_2\ Q_2^n \quad P_b = R_b\ Q_b^n$ (7)

In underground mines the flow is turbulent and therefore n = 2. The above formulas can be written for turbulent flows and their mathematical form will be:

$P_1 = R_1\ Q_1^2 \quad P_2 = R_2\ Q_2^2 \quad P_b = R_b\ Q_b^2$ (8)

The total frictional pressure P is the algebraic summation of frictional pressures corresponding to each branch.

$$P = \sum_{i=1}^{b} P_i \qquad (9)$$

The equivalent resistance of a series circuit Rs, N s^2/m^8 is given by,

$$R_s = \sum_{i=1}^{b} P_i \qquad (10)$$

where:
P_1, P_2, …, P_b is the frictional pressure drop along each branch, (Pa),
R_1, R_2, …, R_b is the resistance on individual branch, (N s^2/m^8),
Q is the airflow volume through the branches, ((m^3/s),
R_s is the resistance for series circuit, (N x s^2/m^8) and
b is the number of branches in the circuit
N is the force in Newten

Parallel Circuit

The schematic of a parallel circuit is presented in the Figure 7 [23]. The pressure drop is the same for each branch.

$P = P_1 = P_2 = \ldots = P_b$ (11)

$Q = Q_1 + Q_2 + \ldots + Q_b$ (12)

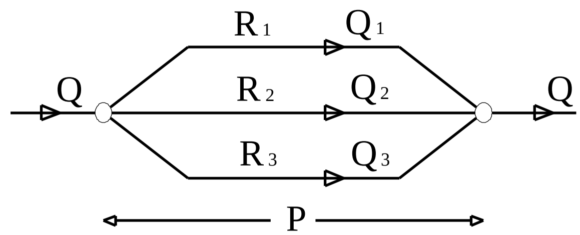


Fig. (3) : Parallel circuit

The general form for frictional pressure drop on each branch is:

$P_1 = R_1 \times Q_1^n \quad P_2 = R_2 \times Q_2^n \quad P_b = R_b \times Q_b^n$ (13)

$Q_1 = (P_1/R_1)^{1/n} \quad Q_2 = (P_2/R_2)^{1/n} \quad Q_b = (P_b/R_b)^{1/n}$ (14)

In underground mines the flow is turbulent and therefore n = 2. The above formulas can be written for turbulent flows and their mathematical forms will be:

$Q_1 = (P_1/R_1)^{1/2} \quad Q_2 = (P_2/R_2)^{1/2} \ldots Q_b = (P_b/R_b)^{1/2}$ (15)

The summation of airflows from all b branches forms the total airflow in the circuit *Q*, m^3/s.

$$Q = \sum_{i=1}^{b} Q_i \qquad (16)$$

The equivalent resistance of a parallel circuit is given by:

$$1/\sqrt{R_p} = \sum_{i=1}^{b} 1/\sqrt{R_i} \qquad (17)$$

where:
Q_1, Q_2, …, Q_b is the volume of air in each branch, (m^3/s)),
R_1, R_2, …, R_b is the resistance on individual branch, (N s^2/m^8),
Q_b is the air flow volume per unit time through individual branches, (m^3/s),
R_p is the resistance for parallel circuit, (N • s^2/m^8) and
b is the number of branches in the circuit

1.4 Analytical Solution

The analytical solution for simple ventilation networks is based on Kirchhoff's Laws and considers that the minimum number of meshes m needed to be selected for calculation is: m = b – j +1, where: m is the number of meshes, b is the number of branches and j is the number of nodes. With the m number of meshes selected there will be , j – 1 junction equations (Kirchhoff's First Law) and b – j + 1 mesh equations (Kirchhoff's Second Law). The final results are coming from a system of "b" equations formed for a circuit that has "b" branches. The limitation of this method is the complexity level of calculations when it is applied to a complex mine network.

1.5 Complex Ventilation Networks (Hardy - Cross Method) [23]

When a flow Q (m^3/s) passes through an airway of resistance R ($N \cdot s^2/m^8$), the frictional pressure drop developed is given by:

$$P = R\ Q^n \quad (18)$$

In the Hardy-Cross method of analysis, any value for the airflow Q and pressure drop P can be written as:

$$Q = Qa + \Delta Q \quad (19)$$

$$P = Pa + \Delta P \quad (20)$$

where:
Qa is the initial estimation of the airflow, (m^3/s),
ΔQ is the error in the initial estimation, (m^3/s),
Pa is the pressure drop corresponding to *Qa*, (Pa) and
ΔP is the error in pressure drop corresponding to ΔQ, (Pa)

Fig. 4 [23] shows a flow pressure relationship applied to the Hardy - Cross analysis of networks. This figure indicates that the slope for the curve is $\Delta P / \Delta Q$ and at the limit dP / dQ. If one differentiates the equation P = R x Q^n based on Q, we get the following relation :

$dP / dQ = n \times R \times Q^{n-1}$

For the estimated value Qa:

$\Delta P / \Delta Q = n \times R \times Q_a^{n-1}$

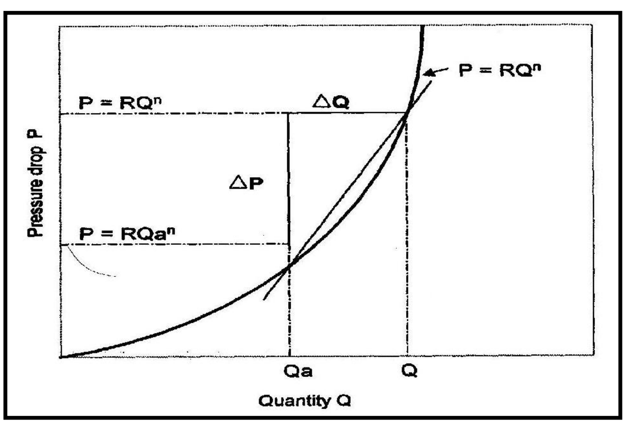


Fig. (4) : Pressure vs airflow variation at small increments[23]

From Fig. 4, $\Delta P = P - P_a$, and if we substitute the values:

$\Delta P = R\,Q^n - R\,Q_a^n$

$\Delta Q = \Delta P / n\,R\,Q_a^{n-1}$

$$\Delta Q = (Q^n - Q_a^n) / (n\,Q_a^{n-1}) \quad (21)$$

The above equation is for one airway. In the case of an underground mine there will be branches that will form a closed mesh within the network. In this case the error in the frictional pressure is given by:

$$\Delta P = (1/b)[\sum_{i=1}^{b}(R_i Q_i^{ni} - R_i Q_{ia}^{ni})] \quad (22)$$

with the mean slope of the curve given by,

$$(1/b)[\sum_{i=1}^{b}(nR_i Q_{ia}^{ni-1})]$$

The general form for the mesh correction factor ΔQ_m can be written as,

$$\Delta Q_m = [\sum_{i=1}^{b}(R_i Q_i^{ni} - R_i Q_{ia}^{ni})] / [\sum_{i=1}^{b}(nR_i Q_{ia}^{ni-1})] \quad (23)$$

The numerator of the above formula gives, Pi = $R_i x Q_i^n$ and represents the frictional pressure drop on the branch i. Kirchhoff's Second Law states that, $Q = \sum_{i=1}^{b} P_i = 0$, and, if we substitute the above relationship in equation 23 then:

$$\Delta Q_m = -[\sum_{i=1}^{b}(R_i Q_i^{ni})] / [\sum_{i=1}^{b}(nxR_i Q_{ia}^{ni-1})] \quad (24)$$

The sign of these sums is very important and has to be carefully analysed. Also, in the calculation the frictional pressure drop is always positive in the direction of the flow. Mine ventilation networks have many branches and therefore the suggested rule for sign convention is that the clockwise direction on each mesh should be positive. The final relationship for ΔQ_m has to consider fans and natural ventilation pressure, and is given by:

$$\Delta Q_m = -[\sum_{i=1}^{b}(nR_i Q_{ia}^{ni-1} - S_{fi})] \quad (25)$$

where:
P_{fi} is pressure of the fan that has Qia in the branch i, (Pa)and
S_{fi} is slope of the fan characteristic in branch i, (Pa)

With the iteration process continuing, the mesh correction factor ΔQ_m decreases in all branches. When its value approaches the accuracy level that is considered practical (as close to zero as possible) the iteration stops. The above formulas are characterized by the index n that is a function of the type of flow. The normal values for n are considered to be between 1.8 and 2.2 (with potential to be 1.0 if the flow is laminar). For underground mines n = 2 (turbulent flows) which gives a good estimate when used in equation 25. In the process of calculations there may be a need to fix some of the air flows (fan sizing or stopping calculations) on a particular branch. In these cases the flows will be removed from the Hardy - Cross analysis.

2. Radon and Radon Daughter Level Prediction

Most of the underground operations that have to consider radiation as criteria in their ventilation planning are uranium mines and waste nuclear repositories. The main source of radiation comes from radon. Radon has three natural species, presented in Table 1.

Table 1: Radon species (24).

Radionuclide	Historical name	Decay Series	Half Life
radon - 222	Radon	Uranium - 238	3.82 days
radon - 220	thoron	Thorium - 232	55.6 sec
radon - 219	actinon	Uranium - 235	5.96 sec

From these three isotopes, Radon 222 is the only one that is considered to have a major impact to workers because of its half life of 3.82 days. Radon-222 is produced by the radioactive decay of radium 226, itself a decay product of uranium. Radium has a long half life of 1622 years and thus acts as an effectively constant source of radon which has a relatively short half-life of 3.82 day. The decay of radon into its four successive short lived radioactive daughter products may become trapped in the human respiratory system where they constitute a health hazard due to the ionizing alpha radiation associated with their decay. The product of the decay of radon is shown in Fig.5.

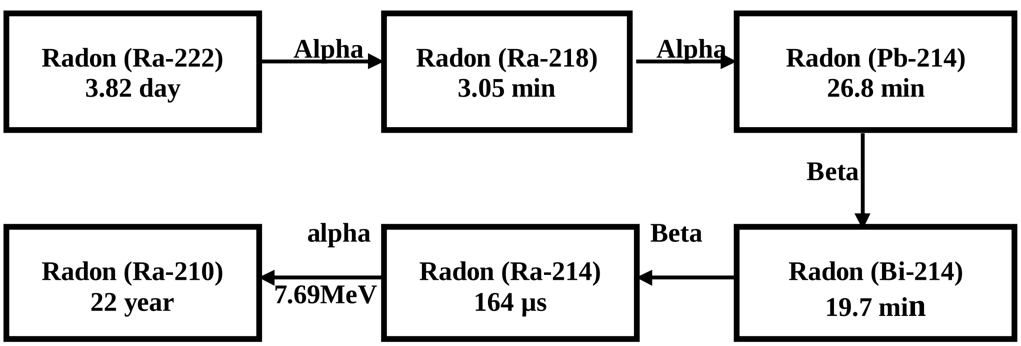


Fig. (5) : The daughter product of the decay of radon

Concentrations of the short-lived radon daughter products are measured in working levels (WL). One working level is 1.3 x 10^5 MeV of potential alpha energy per liter of air and it corresponds to an activity concentration of 100 $pCil^{-1}$ = 3700 Bqm^{-3}. Exposure to radon daughters is expressed as the product of working levels and time, the recognized unit being the working level month (WLM). One WLM results from exposure to a radon daughter concentration of one WL for one working month (176 hours). The maximum permissible annual occupations exposure has been specified as 4 WLM (25).

2.1 Radon Flux into The Mine Atmosphere

The flux of radon from ore surfaces into the mine atmosphere is determined by the rate of production of diffusing radon and the rate at which interstitial radon migrates to exterior surfaces. The radon source strength is in turn determined by the rate at which radon is produced through the decay of radium and by the fraction often termed "emanation coefficient" of the radon which escapes the rock matrix and is free to diffuse in the pore spaces. A "typical'[1] emanation coefficient of 0.2 has often been used to model radon sources from uranium mines(.26)

The radon production rate in a porous radium-bearing material can be expressed as[27].

$$Q = [A_{Ra}]\ \rho E / P \times \lambda\ = -\beta_{max}\ E / P\ =\ \beta /\ P \quad (26)$$

where

E is the emanation coefficient,

P is the porosity (ratio of pore volume to total volume),

Q is the radon production rate (Bq/s per m^3 of pore space),

$[A_{Ra}]$ is the radium - 226 concentration (Bq/kg),

ρ is the bulk density (kg/m^3),

λ is the radon decay constant (2.1×10^{-6} /s) and

β is the emanating power ($Bq/s.m^3$)

β_{max} is the emanating power assuming all available radon is released to the pores. The rate of diffusion from a plane source is given by [27].

$$C = C_o\ [\ 1- \exp\ (-z / \sqrt{D / \lambda P}\ )\ ] \quad (27)$$

Where:

z is the perpendicular distance (m) from the source,

C is the radon concentration at distance z (Bq/m^3),

C_Q is the radon concentration in the plane source [$C_o = q/\lambda$ (Bq/m^3)] and

D is the bulk diffusion coefficient (m^2/s)

2.2 Growth of Working Levels

The radon daughter concentration in a given airway consists of two components; radon daughters resulting from decay of radon from previous airways WL_1 and radon daughters resulting from the decay of radon originating in that particular airway WL_2.. The value of radon daughters WL_1 and WL_2 can be calculated from the following equations [28 and 29]:

$$WL_1 = K\ C_o\ (T_{tr})^{y} \quad (28)$$

$$T_{tr} = T_r + T \quad (29)$$

$$T_r = \sqrt[0.86]{E_r / (3700 K)} \quad (30)$$

Where:

E_r is the equilibrium ratio between radon and its daughters at the node ≈ 0.275,

K is the proportionality constant, K=6.15x10^{-6},

T is the travel time for the air [T=V(m^3) / Q (m^3/min)],

T_r is the radioactive age of the air flows through the branch (min) [$T_r = \sqrt[0.86]{E_r / (3700 K)}$],

T_{tr} is the total radioactive age of the air at the end of the branch (min),

Q is the branch flow (m^3/min)and

V is the branch volume (m^3)

The values of radon daughter growth parameters K, y and E_r are given in Table 2 [28].

Table 2: values of radon daughter growth parameters K, y and E_r [28]

Time range (min)	*K*	*y*	Ratio E_r
0.0 - 41.45	6.15 E-6	0.86	0.0 – 0.55
41.45 – 112.0	23.15 E-6	0.50	0.55 – 0.91
112.0 – 220.0	137.21 E-6	0.12	0.91 – 0.99

$$WL_2 = (60\ K\ J\ P\ T^{1.86})/(1.86\ A) \quad (31)$$

$$J = (C_2 - C_1)\ Q / (P\ L) \quad (32)$$

Where:

A is the cross sectional area of the tunnel (m^2),

J is the emanation rate, (Bq $m^{-2}s^{-1}$),

C_2, C_1 are the final and initial radon concentrations, (Bq/m^3),

Q is the volume of air, (m^3/s),

P \is the perimeter of the mine opening, (m),

L is the length between the two measuring points, (m) and

T is the travel time for the air [T=V(m^3)/Q (m^3/min)]

Emanation rates vary with the rock porosity and some of the values are presented below [28]:

- high porosity (sandstones): 20 (Bq $m^{-2}s^{-1}$)
- intermediate porosity (shales): (2 – 5) (Bq $m^{-2}s^{-1}$)
- low porosity (Elliot Lake conglomerates): (0.05 – 0.0) (Bq $m^{-2}s^{-1}$)
- igneous rocks: (0.0002 – 0.002) (Bq $m^{-2}s^{-1}$)

McPherson [23] proposed typical values for the case of ^{222}Rn emanating from uranium mines of A_{Ra} = 30 Bq kg^{-1}, D = 1.2x10^{-6} m^2s^{-1}, E = 0.2, P = 0.5, β = 0.85 [Bq/($s^{-1}m^{-3}$] and ρ = 2.65x10^3kg/m^3. Using the above equations, a basic computer program was written to calculate the values of radon decay products concentration in units of working level, pressure drop, air flow and fan static pressure required to reach the permissible concentration level of radon in each point in the mines. The flow chart of the general structure of computer program (RADVENTPROG) is shown in Fig. (6). Inputs to the main program come in the form of control codes. Other inputs come through the subroutines and are transferred to other subroutines through subroutine arguments. Subroutine RADCAL to calculate radon daughter concentration u, Subroutine ARBOL chooses the chords and sets up the meshes using the theories outlined in the network analysis section and the subroutine PROCA solves the mine network problem using the Hardy Cross method. The consistency and reliability of the present predictions were evaluated by comparing the obtained results using the developed computer program with the corresponding measured values obtained by others [19, 21] and with those calculated using REDES software[20, 21]

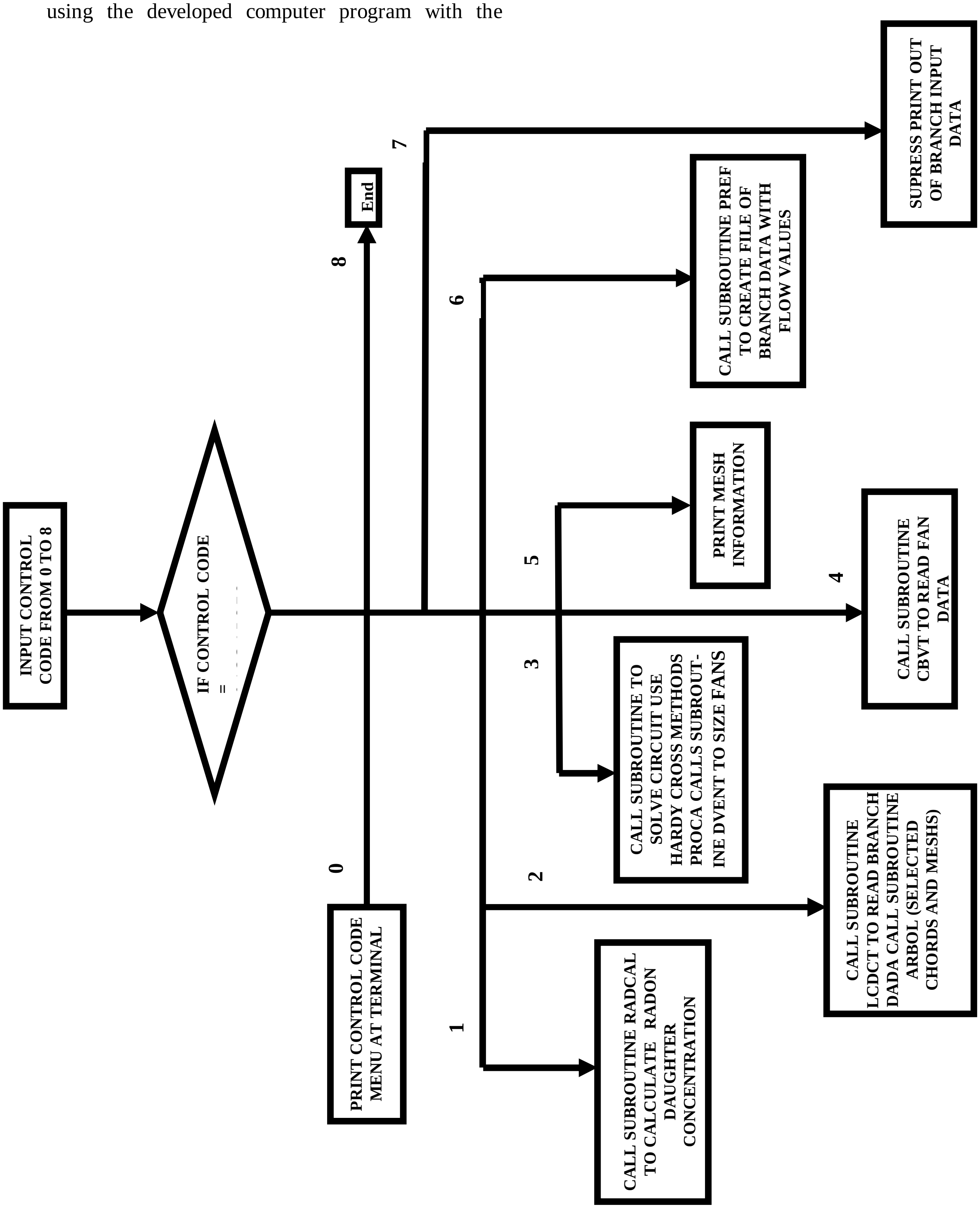


Fig. (6) : Flow chart of general structure of RADVENTPROG.

Case Study

In addition to the workers in uranium mines, the staff of other underground mines, such as workers in underground phosphate mines, can be exposed to ^{222}Rn and its progeny. According to previous studies through the Egyptian national program for safety, the values of radon decay products in units of working level (WL "1WL = 1.2E-6 J/m^3 ") ranged from 0.67-1.28 in some phosphate mines in the eastern desert of Egypt [(6)] . These levels are much higher than the recommended international limit for the workers which is 0.3 WL [(7)] . These high levels are due to bad ventilation system in those phosphate mines. The control of radon and radon decay products in underground is mainly achieved by an efficient ventilation system. The ventilation in underground may be natural or mechanical. Depending upon a study carried out, natural ventilation was studied in some phosphate underground mines in Egypt. The values of radon decay products concentration in units of working level show higher values than that recommended internationally which means that natural ventilation is not the proper control methods [(5,6)]. So mechanical ventilation is considered as the best proper control method [(6,8)] to decrease radon decay products concentration to the recommended levels [(9,10)]. The proposed computer program is used to calculate the values of radon decay products concentration in units of working level, the air flow rate required of the mechanical ventilation to reach the acceptable radon concentration relative to the recommended levels, fan static pressure and the approximate electrical power consumption cost for two underground phosphate mines. The network diagrams for the two studied mines are shown in Figs. (7 and 8). The estimated pressure drop through each branch, and the required air flow to reach the recommended level for radon concentration at each point for the two studied tunnels are tabulated in Tables (3,4,5 and 6) .

From the tables it could be seen that the calculated values of radon decay products concentration in units of working level are smaller than the corresponding measured one. This could be due to the following

- The equations used in this study to model the concentrations of radon daughters in mine atmospheres are derived directly from the laws of radioactive decay and ventilation dynamics, where it is assumed that no other removal mechanisms which could influence the concentrations are operable. In a real mine however an additional variables such as the plateout of unattached (to aerosols) daughters to mine surfaces and the deposition of attached daughters also influence the ultimate airborne concentration. So a future studies and experimental measurements are required to characterize these effects
- It is difficult to predict an accurate values for radon diffusion rate science it depends on a very large number of different parameters, so an accurate prediction values are very difficult to make [(13)].
- .Aside from diffusion and transport directly from the rock walls, there are numerous other sources of radon in an underground mine atmosphere which are not taken into consideration, some of which may be very substantial. Blasting will cause radon to be released immediately on rock fracture, and will also affect radon influx due to stress redistribution. Piles of loose muck will emanate radon, and mucking activities greatly enhance radon production.

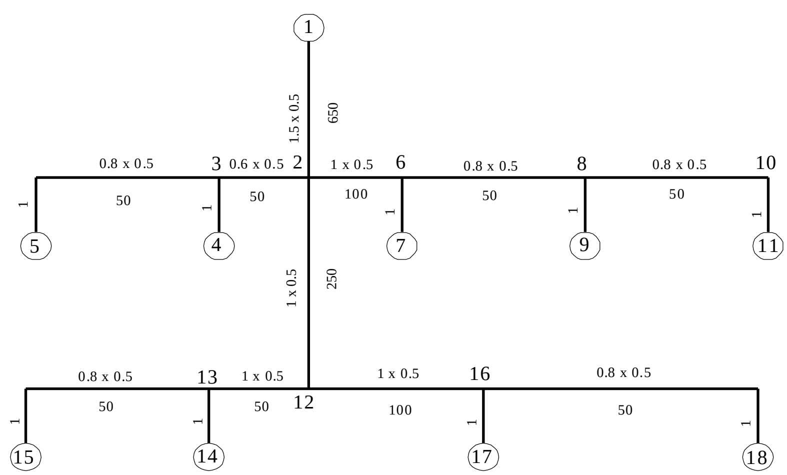


Fig. (7) : Schematic of the studied points, their distance from the opening as well as the duct sizing for Qusser Yonus mine (Dimensions in meter).

Table (3): The calculated air flow (Q) and pressure drop (ΔP) required at each point to reach the recommended international limit (WL) for the workers for Qusser Yonus mine.

Branch		length m	Area m^2	Q(i,j) m^3/h	pressure drop (ΔP) Kpa
Initial node i	Final node j				
1	2	650	0.75	23200	0.723
2	3	50	0.4	3000	0.124
2	12	250	0.5	12400	0.238
3	4	1	0.4	1400	0.362
3	5	50	0.4	1600	0.315
2	6	100	0.5	7800	0.072
6	7	1	0.4	1700	0.243
6	8	50	0.4	6100	0.037
8	9	1	0.4	2300	0.206
8	11	50	0.4	3800	0.160
12	13	50	0.5	6300	0.035
13	14	1	0.3	3100	0.125
13	15	50	0.4	3200	0.054
12	16	100	0.5	6100	0.416
16	17	1	0.4	3000	0.018
16	18	50	0.4	3100	0.029

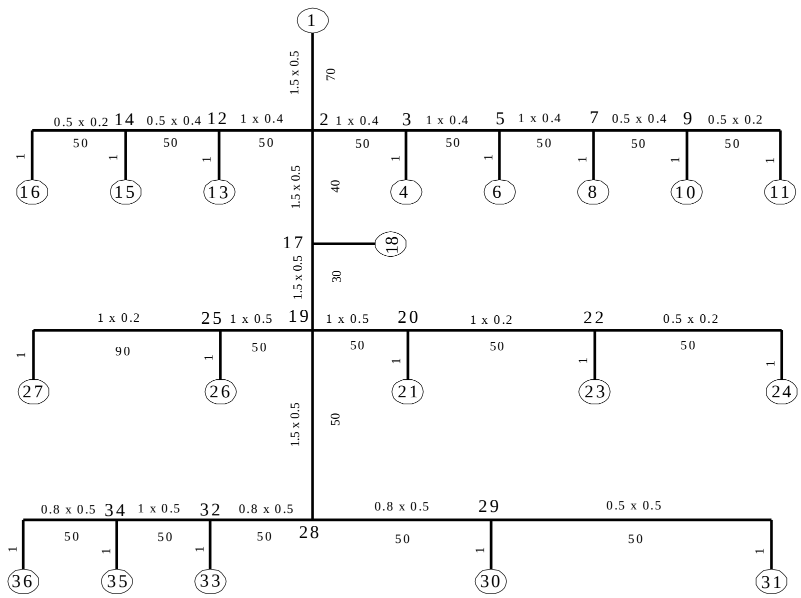


Fig. (8) : Schematic of the studied points, their distance from the opening as well as the duct sizing for Hamraween mine (Dimensions in meter).

Table (4): The calculated values of WL compared with the measured ones at each point and the required air flow rate required to reach the recommended international limit (WL) for the workers for Qusser Yonus mine.

Location of study point	Distance from opening point (1)	Measured WL	Calculated WL	Required flow rate (m^3/h)
4	700	0.481	0.437	1400
5	750	0.568	0.474	1600
7	800	0.596	0.534	1700
9	850	0.641	0.567	2300
11	900	0.701	0.617	2800
14	950	0.743	0.668	3100
15	1000	0.748	0.675	3200
17	1050	0.765	0.689	3000
18	1100	0.786	0.702	3100

Table (5): The calculated air flow (Q) and pressure drop (ΔP) required at each point to reach the recommended international limit (WL) for the worker for Hamraween mine.

Branch		Length m	Area m^2	Q(i,j) m^3/h	Pressure drop (ΔP) Kpa
Initial Node i	Final node j				
1	2	70	0.75	34500	0.143
2	3	10	0.32	6800	0.137
2	12	30	0.32	3900	0.218
2	17	40	0.75	23800	0.154
3	4	1	0.12	1000	0.209
3	5	40	0.32	5800	0.028
5	6	1	0.06	1300	0.179
5	7	20	0.32	4500	0.016
7	8	1	0.12	1400	0.171
7	9	40	0.20	3100	0.037
9	10	1	0.12	1500	0.135
9	11	40	0.80	1600	0.133
12	13	1	0.10	1100	0. 131
12	14	30	0.20	2800	0.019
14	15	1	0.10	1200	0.113
14	16	60	0.80	1600	0.112
17	18	1	0.12	1600	0.187
17	19	30	0.75	22200	0.032
19	20	20	0.24	4300	0.027
19	25	50	0.24	4100	0.129
19	28	50	0.75	13600	0.062
20	21	1	0.10	1500	0.125
20	22	40	0.12	3300	0.096
22	23	1	0.20	1600	0.033
22	24	40	0.08	1700	0.023
25	26	1	0.16	1600	0.025
25	27	90	0.12	2500	0.075
28	29	10	0.32	5000	0.045
28	32	60	0.32	8300	0.056
29	30	1	0.13	2500	0.032
29	31	100	0.24	2500	0.053
32	33	1	0,24	2500	0.051
32	34	100	0.24	5800	0.072
``34	35	1	0.24	2800	0.045
34	36	50	0.24	3000	0.055

Table (6) : The calculated values of WL compared with the measured ones at each point and the required air flow rate required to reach the recommended international limit (WL) for the workers for Hamraween mine.

Location of study point	Distance from opening point (1)	Measured WL	Calculated WL	Required flow rate (m^3/h)
4	60	0.358	0.328	1000
6	100	0.381	0.351	1300
8	120	0.384	0.354	1400
10	160	0.402	0.367	1500
11	200	0.421	0.397	1600
13	90	0.375	0.348	1100
15	120	0.387	0.353	1200
16	180	0.417	0.383	1700
18	100	0.393	0.361	1600
21	130	0.393	0.373	1700
23	180	0.421	0.371	1600
24	230	0.425	0.383	1700
26	180	0.398	0.362	1600
27	270	0.458	0.426	2500
30	180	0.441	0.401	2500
31	290	0.489	0.445	2500
33	240	0.478	0.435	2500
35	290	0.512	0.473	2500
36	340	0.572	0.572	3000

Depending upon the location of study point from the opening the air flow rate ranged from 1000 to 3000 m^3/h for Hamraween mine, 1400 to 3200 m^3/h for Qusser mine. Static pressure, air flow rate and the approximated electrical power consumption of the exhaust fan for each studied case are tabulated in Table 7 against the corresponding values calculated using REDES software [20,21]. From this table it could be noticed that there is a good agreement between the corresponding values.

However the estimated approximate annual electrical power consumption which may reach about 70000 kWh per tunnel in addition to initial and maintenance cost , represent a major problem for some underground work when it is not so preferable such as in case of phosphate mines. The workers health is considered as a pushing factor to develop such expensive radiation safety measure.

Table (7) : Fan static pressure, fan air flow rate and electrical running power consumption required to reach the recommended international limit (WL) for the worker for the two studied mines.

Mine	Fan air flow rate (m^3/h)		Fan static pressure drop (pa)		Approximate annual electrical power consumption per tunnel kWh	
	(1)	(2)	(1)	(2)	(1)	(2)
Hamraween	34500	37000	700	750	53000	61000
Qusser Youns	23200	25000	1350	1500	60000	70000

(1) Values calculated using the present model
(2) Values calculated using REDES software

Conclusion

As a part of comprehensive study, a computer model for the calculation of ventilation parameters has been developed and verified to applied to underground uranium mines environment. Ventilation parameters e.g.: pressures and air flow rate have been calculated to maintain the safe levels of radon daughter in underground mines for workers protection against radiation. The results of the calculations have been evaluated and compared with similar studies and good agreement is demonstrated. The present code is considered as an available Egyptian tool for regulatory evaluation of radiological safety in mines. With the present code, it is possible to calculate the safety limits of ventilation parameters at each exhaust point in the mines which is not possible in the REDES code. In spite of the important role of natural ventilation, which is sufficient to rely upon in various cases, mechanical ventilation is necessary to reduce the airborne radioactivity level to the recommended values.

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