MEASUREMENTS OF NATURAL RADIOACTIVITY IN AN UNDERGROUND HYDROELECTRIC POWER PLANT

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Abstract. In underground working places, especially when ventilation is not properly regulated, large amounts of natural radioactivity can be found. This can give rise to potential exposures of non-negligible magnitude. Direct measurements of gamma radiation and radon were carried out during excavation works for the construction of an hydroelectric plant in the north of Italy. After the construction of the plant, in order to reduce radon concentrations and to improve ventilation effectiveness, the main entry gate was motorized and automated. Then, in order to find the optimal speed for the fans located in the galleries and in the power plant, radon and airflow velocity were measured. Correlation data between airflow and radon concentrations were found. An automatic regulation system has been set up using air velocity detectors and slightly modifying the software for the control and regulation of the power plant. Measurements must be made in order to identify radon sources and evaluate quantitative contributions as a function of ventilation. Underground hydroelectric plants are provided with entry galleries as well as secondary galleries from which radon coming out from the soil and the walls can exhale in quantities that depend on the contents of ^{226}Ra in the rocks and in the building materials. Other radon sources are the water coming out from the walls of the galleries and the water in the deep well located at the bottom of the power plant. Geological studies and mathematical models are useful means for the analysis of the relative contributions of the main sources as well as for the prediction of the effects deriving from modifications of the hydroelectric plant ventilation system or resulting from other important structural changes.

KEYWORDS: hydroelectric plant; radon; gamma radiation; galleries; building materials.

1. Introduction

Very high radon concentrations can be found in underground working places where ventilation is absent or not properly regulated. In addition very high gamma dose rates can be measured near rocks with high radioactive content.

During excavation works for the construction of an hydroelectric plant in the north of Italy a program of environmental monitoring, including direct measurements of gamma radiation, radon and thoron, was planned and carried out in order to reduce exposures of workers.

The galleries of the hydroelectric plant are long (several kilometers) and have small cross sections giving rise to high exhalation surfaces. Radon and thoron concentrations depend on the dimensions of exhalation surfaces as well as the ventilation rate, the physical constitution of building materials, the hydrogeological and lithostratigraphical properties of underground rocks [1] [2] [3] [4] [5] [6] [7], the contribution of other sources [8] [9] [10] such as the water inside the ground or gushing out from the walls as well as the water in underground wells. High radon concentrations and gamma dose rates can be found where rocks have high radium or uranium content. On the other hand emanation rates from the soil depend on particle size, moisture, subsoil porosity and diffusion properties. Also local climatic and meteorological properties, such as moisture, rain, temperature, winds and barometric pressure can influence radon or thoron accumulation inside underground places.

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Geological surveys and analysis, measurements, both instantaneous and time integrated, as well as mathematical models were used in order to study the reasons for radon accumulation inside the power plant. Radon concentrations have been measured and calculated as a function of ventilation rate and water flow from the walls as well as other important physical properties. Based upon the results of these studies the work director decided to improve ventilation effectiveness as well as to automate the main entry gate of the power station.

2. Description of working places

A schematic description of Pont Ventoux - Susa hydroelectric power plant is given below. This plant, with a nominal electric power of 150 MW, uses the water of Dora Riparia river, with a water flow between 0 and 33 m^3/s, and partially the water of Rio Clarea. Its construction began in the year 1996 and ended in the year 2005.

This plant is mainly composed of the following elements:

- Seizure and derivation works
  Pont Ventoux seizure works
  Pont Ventoux - F2 derivation gallery (length 7000 m - internal diameter 4,05 m - external diameter 4,75 m)
  F2 - Clarea derivation gallery (length 7000 m - internal diameter 4,05 m - external diameter 4,75 m)
- Val Clarea reservoir (volume 560000 m^3)
- Adduction works
  Clarea - F4 adduction - derivation gallery (length 4100 m)
  Piezometric upper well
  Penstock (length 1300 m, diameters 3,5 m - 3,2 m - 2,8 m)
- Main power station (51 m x 18 m x 49 m) with entry gallery (length 1200 m), escape gallery (length 400 m), lower well (length 530 m)
- Return works
  Return gallery (length 1600 m)
  Susa reservoir (volume 420000 m^3).

The underground power station of the Pont Ventoux - Susa hydroelectric power plant, where electric power is generated using two Voith Siemens 75 MW turbines (17 m^3/s - 750 revolutions per minute), has six levels with different depths communicating with each other through a central opening. The sixth level is 495 metres above sea level, the fifth level is 489,8 metres above sea level, the fourth level is 485 metres above sea level, the third level is 481,8 metres above sea level, the second level is 477,3 metres above sea level and the first level is 471,5 metres above sea level. The sixth level is the level nearest to ground and the first level is the deepest one.

Radon measurements were performed in the galleries of the power plant, inside the power station, at the six levels, and in the entry gallery, both near the 160 m^3 tank and 100 metres before. This tank is located in the pump room, in a widening located just before the main building entrance, only few metres distant from the sixth level. The mean monthly permanence period of workers near pump room is less than 10 hours per month. The sixth level is mainly a transit room and it communicates directly with the entry gallery.

The main ventilation ducts are located after the main entry gate in the entry gallery. The entry gate must remain mostly in close position. It is opened, temporarily, only when cars or trucks must enter into the gallery. It remains in the open position only for 4,5 minutes and then it is automatically closed. The ventilation system is switched off only when the entry gate is open.

Excavation works in the galleries of the hydroelectric plant were done initially using both full face tunnel boring machine (TBM) and traditional techniques with explosive (drilling and blasting). In the last five years of excavation only drilling and blasting techniques were used.

In order to ventilate galleries and reduce gases and radon concentration a long duct from gallery exit to excavation front was used. This duct was prolonged every day when excavation works were progressing. Intermediate wells and secondary entrances were used in long galleries (Pont Ventoux - F2 gallery, F2 - Clarea gallery, Clarea - F4 adduction gallery).

3. Description of monitoring works inside the galleries and the power station

Measurement procedures consist mainly of
- measurements of instantaneous radon concentrations
- measurements of radon concentrations averaged over few hours
- measurements of long term mean radon concentrations
- measurements of radon concentrations in water
- measurements of gamma dose rate
- measurements of air flow inside the galleries.

Measurements of radon concentrations giving the averaged value over few hours provide the more precise mean to get diurnal exposure. These surveys provide information about the diurnal working period, both in the power station and in the galleries, when the ventilation rate changes because of the opening of the main entry gate. Both passive etched track radon detectors and electret chambers were used in order to get the long term mean radon concentration.

Temperature, humidity and barometric pressure were measured using a portable digital instrument in order to study the dependence of radon concentrations on meteorological factors. Air flows inside the galleries were measured with an hot wire anemometer in order to evaluate the correlation between radon concentrations and ventilation rate.

Surveys of radon concentrations in the water, both inside the galleries and the deep well in the first level of power station, have been performed in order to get information about radon sources and radon migration processes.

Gamma radiation was measured with Eberline ESM FH 40 GL 10 proportional counter that gives equivalent ambient dose rates with a resolution of 1 nGy/h, has an energy range from 30 keV to above 3 MeV and minimum measurable values equal to 10 nGy/h.

4. Measurements inside the galleries with excavation works in progress

Radon concentrations ranging from 2900 Bq/m^3 to 6400 Bq/m^3 were measured by local authorities in the year 1998 inside the Pont Ventoux - F2 derivation gallery during the excavation works for the construction of the Pont Ventoux - Susa hydroelectric power plant when there was no adequate ventilation system. Values ranging from 780 Bq/m^3 to 12000 Bq/m^3 were found in 1998 inside the entry gallery of the power station when ventilation was temporarily switched off because of the great quantities of water gushing out from the rocks. While concentrations ranging from 430 Bq/m^3 to 980 Bq/m^3 were measured with ventilation switched on. Similar results (concentrations up to 1600 Bq/m^3) were obtained in subsequent surveys made inside the entry gallery from july 1998 to february 2000. Other measurements, made in the same period of time, were performed in the F2 derivation gallery, Clarea adduction gallery, F4, F5 and Susa galleries, when excavation works were in progress. Interesting results were found in the F2 derivation gallery where extremely variable results, depending on ventilation, were found. The highest values, near 6350 Bq/m^3 in case of short measurements (one hour) and near 15000 Bq/m^3 in case of long term (10 weeks) surveys, were measured with ventilation switched off, while the smallest values, near 100 Bq/m^3, were found with fans at the greatest speed.

In the period from 2003 to 2005, when works ended, systematic measurements inside the galleries during excavation activities were taken every three months in order to reduce exposures. These monitoring activities were requested by local authorities.
Measurements were taken both near the two excavation fronts and the two entries of the Pont Ventoux - F2 derivation gallery.

Near Pont Ventoux entry radon diurnal concentrations ranging from 223 Bq/m^3 to 918 Bq/m^3 were measured when ventilation was switched on and fans provided an air flow approximately equal to 18 m^3/s. While with long term detectors, exposed approximately for three months, concentrations ranging from 141 Bq/m^3 to 874 Bq/m^3 were found. The highest value was measured in a period of time, from august 2005 to september 2005, during which the ventilation was initially switched off for technical reasons (august 2005) and then switched on again (september 2005).

Near the other entry diurnal concentrations variable between 30 Bq/m^3 and 490 Bq/m^3 were found. With long term detectors, exposed approximately for three months, radon mean concentrations between 35 Bq/m^{3}and 454 Bq/m^3 were measured, all below the action level equal to 500 Bq/m^3.

Few meters before the excavation front in the gallery part starting from Pont Ventoux radon diurnal concentrations between 105 Bq/m^3 and 780 Bq/m^3 were found with ventilation switched on and air flow roughly equal to 18 m^3/s. While with long term detectors, exposed approximately for three months, concentrations ranging from 120 Bq/m^3 to 763 Bq/m^3 were measured. The highest value was found in a period of time, from july 2004 to october 2004, during which the ventilation was switched off for a little more than one month due to technical problems.

Near the other excavation front diurnal concentrations variable between 105 Bq/m^3 and 529 Bq/m^3 were found with a nominal air flow equal to 12 m^3/s. While with long term detectors, exposed approximately for three months, radon mean concentrations between 200 Bq/m^{3}and 868 Bq/m^3 were found. Even in this case the highest value was obtained in the period of time from july 2004 to october 2004.

Comparing the results of measurements made from 2003 to 2005 with the concentrations measured in the year 1998 inside the Pont Ventoux - F2 derivation gallery it can be deduced that adequate ventilation is indispensable for achieving acceptable radon concentrations inside galleries.

In order to prevent exposures due to gamma radiation two action levels for gamma dose rate were set: a warning level equal to 0,6 µGy/h and an alarm level equal to 3,7 µGy/h. During excavation works the lower action level was rarely exceeded while the higher action level was never exceeded.

5. Results of surveys inside the power station and the entry gallery

Radon sources inside the power plant are mainly the exhalation from the soil and the building materials of both the entry gallery and the main building, the water gushing out from the rocks in the entry gallery and the water inside the deep well in the first level.

The entry gallery has a rectangular lower section and a semicircular upper section. Transversal dimensions of this gallery range from 7 to 8,5 meters. The walls are made mainly of beton (15 - 20 cm in thickness) upon reinforcing metallic bars of an electric welded mesh positioned over the rocks. The walls in the main building are made of beton, 25 cm in thickness, covered by aluminium panels that are 4 mm thick (50 cm far from beton). In the lower levels beton is covered by 40 cm of reinforced concrete.

The rocks of the entry gallery have a medium-low content of radium and other natural radionuclides as can be deduced from measured data of gamma spectrometry (table 1).

Table 1. Content (minimum - maximum value) of U-238 series, Th232 series and K-40 in the rocks of the entry gallery

U-238 series	Th-232 series	K-40
25 - 26,8 Bq/kg	20 - 40,7 Bq/kg	590 - 800 Bq/kg

Radioactive and physical properties of beton, as well as the properties of other building materials, can be measured or found in literature [8] (table 2-1 and table 2-2).

Table 2-1. Content of Ra-226, Th232 and K-40 in some building materials

Building material	**^{226}Ra (Bq/g)**	**^{232}Th (Bq/g)**	**^{40}K (Bq/g)**
Concrete - beton	0,035 (0,01 – 0,12)	0.022	0.27
Aerated concrete	0,045 (0,01 – 0,14)	0.025	0.27
Brick	0,045 (0,015 – 0,06)	0.045	0.6
Gypsum	natural 0,01 (0,003- 0,03) with phosphates 0,4 (0,25 – 0,7)	0.008 0.01	0.15 ----
Granite	0,075 (0,01 – 0,2)	0.1	1.2
Basalt	0,03 (0,004 – 0,45)	0.06	1.1
Marble	0,006 (0,001 – 0,025)	0.002	0.02
Beole	0,06 (0,02 – 0,2)	0.05	1.4
Sand	0,025 (0,001 – 0,2)	0.025	0.52
Limestone	0,01 (0,0015 – 0,03)	0.004	0.03
Porphyry	0,04 (0,025 – 0,05)	0.055	1.35
Slag	0,055 (0,03 – 0,09)	0.05	0.6
Lava	0,4 (0,03 – 1)	0.22	1.7
Tuff	0,2 (0,13 – 0,3)	0.35	1.8
Wood	0,003 (0.0003 – 0,005)	0.003	0.17

Table 2-2. Physical properties of some building materials

Building material	**Porosity**	**Typical density (g/cm^3)**	**Effective diffusion coefficient (10^{-6} m^{2}s^{-1})**
Concrete - beton	10 %	2,4	0,0007
Aerated concrete	48 %	0,65	0,62
Brick	15 %	1,4 - 2,4	0,065
Gypsum	30 - 50 %	0,8 - 1,2	0,53 - 1,7
Granite	0,05 - 1,5 %	2,65 - 2,75	---
Basalt	0,1 - 3 %	2,4 - 3,1	---
Marble	0,1 - 3 %	2,6 - 2,85	---
Pumice - stone	30 - 65 %	0,6	0,4 - 2,5
Sand	10 - 25 %	1,7 - 2,4	0,4
Limestone	10 - 30 %	2,65 - 2,75	0,08
Porphyry	3 %	2,6 - 2,9	0,0014
Slag	25 %	1,8 - 3,8	0,1
Wood	---	0,4 - 1,2	---

Water gushing out from the rocks inside the entry gallery, at an overall rate greater than 0,2 m^3/s, is conveyed in part directly to the 160 m^3 tank located in the entry gallery before the power station and in part, if the distance is greater than 1145 m from the entry, to the deep well in the first level where finally it is pumped to the 160 m^3 tank.

The first monitoring inspection inside the power station was carried out on the 27th of november 2004. Until that day the ventilation system did not work efficiently. Therefore high radon concentrations were found (table 3 and table 4).

Table 3. Instantaneous radon concentrations measured during the first inspection (27/11/2004)

Measurement point	Date Hour	Instantaneous concentration measured with electret detectors	Uncertainty
Near the 160 m^3 tank in the entry gallery measurement point EP1	27/11/04 17.10	1143 Bq/m^3	± 82 Bq/m^3
100 meters before the 160 m^3 tank measurement point EP2	27/11/04 17.40	940 Bq/m^3	± 68 Bq/m^3
First level in the power station measurement point EP3	27/11/04 18.20	995 Bq/m^3	± 72 Bq/m^3
Second level in the power station measurement point EP4	27/11/04 18.50	996 Bq/m^3	± 72 Bq/m^3
Third level in the power station measurement point EP5	27/11/04 19.15	1009 Bq/m^3	± 73 Bq/m^3
Fourth level in the power station measurement point EP6	27/11/04 19.35	1039 Bq/m^3	± 75 Bq/m^3
Fifth level in the power station measurement point EP7	27/11/04 20.12	942 Bq/m^3	± 68 Bq/m^3

Table 4. Time averaged concentrations measured with H chambers and short term electrets during the first inspection (27/11/2004)

Measurement point	Date Hour	Average radon concentration over few hours measured with electret H chambers	Uncertainty
Near the 160 m^3 tank in the entry gallery measurement point H1	27/11/04 14.50 - 21.25	1202 Bq/m^3	± 64 Bq/m^3
First level in the power station measurement point H4	27/11/04 15.10 - 21.25	1024 Bq/m^3	± 57 Bq/m^3
Second level in the power station measurement point H3	27/11/04 15.10 - 21.25	1020 Bq/m^3	± 56 Bq/m^3
Fifth level in the power station measurement point H2	27/11/04 15.10 - 21.25	1054 Bq/m^3	± 58 Bq/m^3

From the results of these measurements we can draw interesting conclusions.

Radon accumulated about uniformly inside the power station. Radon concentration was nearly the same everywhere with the exception of the room with the 160 m^3 tank inside the entry gallery where the radon concentration was a little higher. Likely radon concentration did not change over the working day.

Very short measurements, few hours long, can be made using H chambers and short term electrets. Results are very similar to those obtained making instantaneous measurements using electret chambers in airtight containers.

The reproducibility was very good both for instantaneous measurements and for average concentration surveys with H chambers exposed for few hours. The variation coefficient C_V was equal to 0,0394 for instantaneous measurements and equal to 0,018 for surveys made with H chambers. The same reproducibility was confirmed by the results obtained with further measurement campaigns made from 2004 to 2008 in the same measurement points.

Based upon these results, in order to reduce radon concentrations and to improve ventilation effectiveness, the work director decided to motorize and automate the main entry gate. Radon and air velocity inside the entry gallery were measured in order to get correlation data (Fig. 1-1, 1-2, 1-3, 1-4).

Figure 1-1. Correlation data between radon concentration and airflow velocity (300 m form the entry) when the fans inside the power station were working with an higher speed

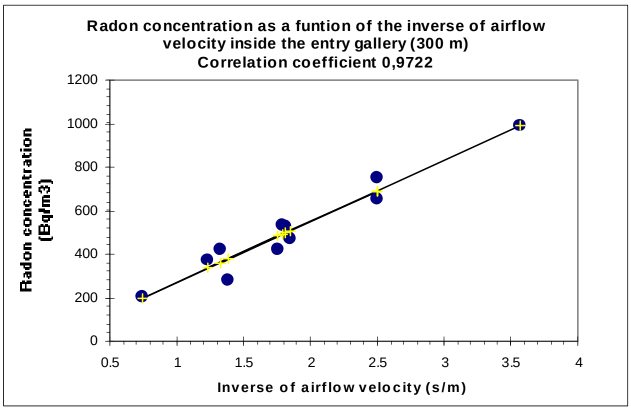


Figure 1-2. Correlation data between radon concentration and airflow velocity (1000 m from the entry) when the fans inside the power station were working with an higher speed

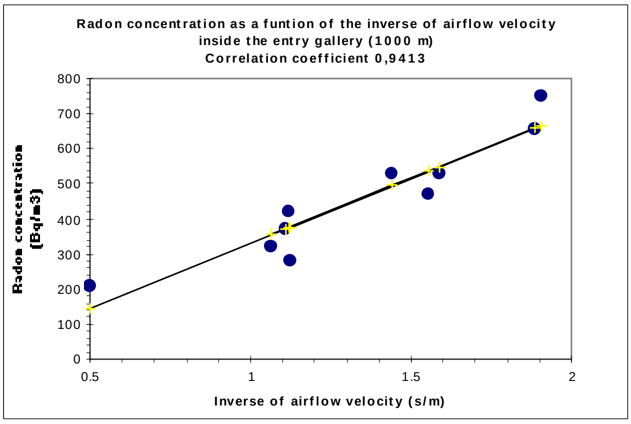


Figure 1-3. Correlation data between radon concentration and airflow velocity (300 m from the entry) when the fans inside the power station were working with a lower speed

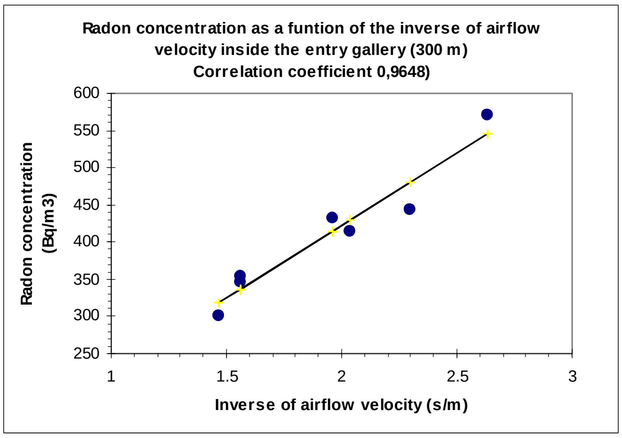
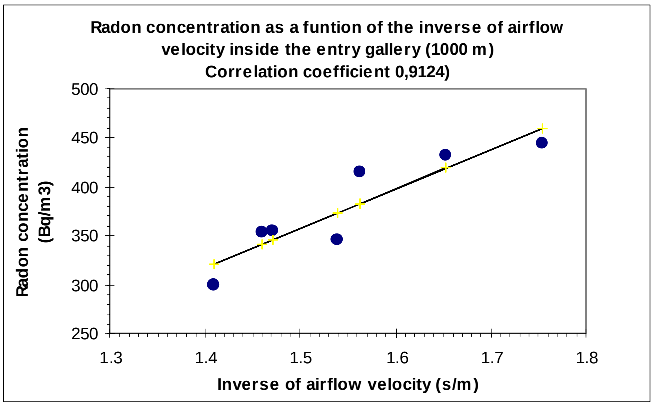


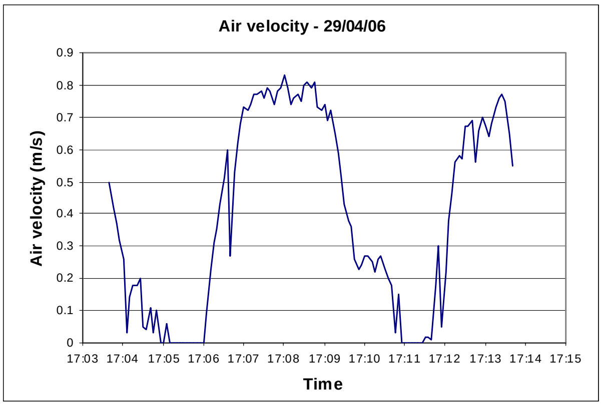
Figure 1-4. Correlation data between radon concentration and airflow velocity (1000 m from the entry) when the fans inside the power station were working with a lower speed



Pressure over the deep well in the first level of the power station increases as the speed of fans in the first and second level of the power station decreases. So the rate of radon exhalation from the water in the deep well decreases. In this way radon concentration decreases even if the ventilation in the power station is lower. Consequently when the fans inside the power station have a lower speed acceptable radon concentrations are achieved with lower airflow velocities in the entry gallery, due primarily to the main fans near the entry gate.

In fig. 2 measured air speed as a function of time is shown in a period during which the main entry gate was opened twice. As can be seen in the figure when the gate is open the ventilation drops down for about 4,5 minutes. During this period of time radon concentration increases momentarily. This is why concentrations averaged over few hours are higher than instantaneous concentrations measured when the main entry gate is close. Radon long term concentrations, measured every three months both with passive etched track radon detectors and with electret chambers, are a little bit lower than concentrations measured during working activities using electret H chambers since the entry gate is opened mainly during daytime.

Figure 2. Air velocity as a function of time when the entry gate was opened twice



In order to precisely set the speed of the main fans an automatic regulation system has been set up. Air speed inside the gallery is measured by two detectors. When air velocity falls below a certain value the speed of the main fans is increased. This is done using the software for the control and regulation of the power station.

Every three months measurements of radon concentrations are performed in order to monitor the situation. Concentrations far below the action level of italian legislation, that is equal to 500 Bq/m^3, are obtained everywhere with the exception of the first level where concentrations are still near action levels. Further surveys were also performed in order to evaluate possible differences between radon concentrations measured when turbines are in operation and when turbines are not in operation but great variations were not found.

Thoron concentrations measured inside the power station were very low. Thoron was absent or in small quantities. Its concentration was smaller than 120 Bq/m^3.

In order to get more information about radon sources in the power station radon concentrations in the water inside the entry gallery and in the water inside the deep well were measured. Concentrations in the water gushing out from the walls of the entry gallery were often between 20000 Bq/m^3 and 45000 Bq/m^3, but sometimes values between 5000 Bq/m^3 and 20000 Bq/m^3 were measured. Concentrations measured in the water inside the deep well below the first level were of the same order of magnitude, but generally a little bit smaller. All these concentrations are typical concentrations often found in underground waters (deep waters have higher radon contents while surface waters have lower radon contents).

The values of gamma radiation dose rate measured inside the power station were always low because in the main building there are no significant gamma radiation sources and cosmic rays are attenuated by the thick layer of rocks.

6. Mathematical models

Considering a system made of many galleries and taking into account only the most significant terms (Fig. 3), in the equation for radon balance in the gallery n there are 5 terms [2].

$$\frac{\partial C_n(t)}{\partial t} = T_1 + T_2 + T_3 + T_4 + T_5$$

- Contributions from walls, floor or ceiling of the gallery $T_1 = \sum_i \frac{F_{lwall,n,i}}{V}$
- Internal sources of radon, such as water that gushes out $T_2 = \frac{1}{V} \cdot F_{g,\text{int},n}$
- Air exchange with the other galleries $T_3 = \sum_i (C_{g,i}(t) - C_{g,n}(t)) \cdot n_{rg,n,i}$
- Air exchange with external environment $T_4 = (C_{out}(t) - C_{g,n}(t)) \cdot n_{r,n}$
- Radon decay $T_5 = -\lambda_{Rn} \cdot C_{g,n}(t)$.

where

$C_{g,n}(t)$ is the average radon concentration at time t in the gallery n; radon concentration in the gallery decreases with a decay constant equal to λ_{Rn}

$C_{g,i}(t)$ is the average radon concentration at time t in the gallery i with which there is an exchange rate equal to $n_{rg,n,i}$ volumes per unit time

$C_{out}(t)$ is radon concentration at time t outside the gallery

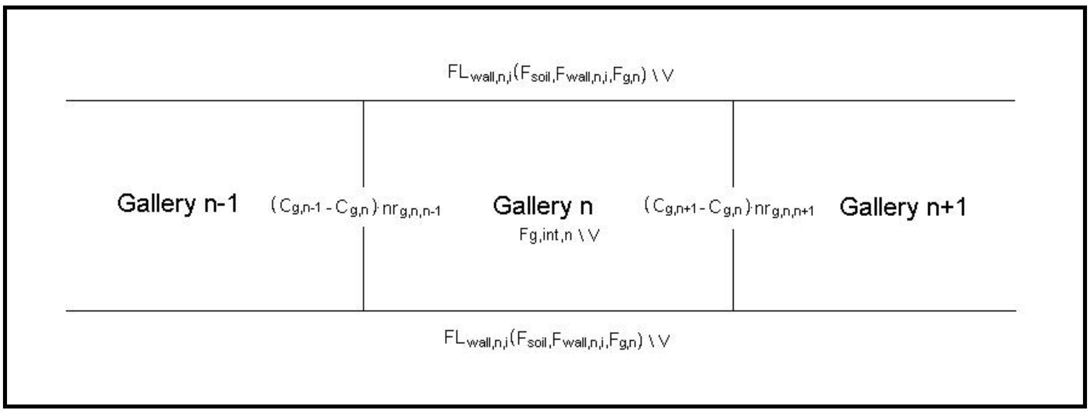
$n_{r,n}$ is the air exchange rate of the gallery with external environment

$Fl_{wall,n,i}$ is the contribution due to radon exhalation from wall/floor/ceiling i that is a function of radon source terms in the soil (F_{soil}), in the walls ($F_{wall,n,i}$) and in the gallery n ($F_{g,n} = T_1 + T_2 + T_3 + T_4$)

V is the volume of the gallery

$F_{g,int,n}$ is the activity per unit time produced by sources in the gallery (typically water gushing out)

Figure 3. Main radon source terms in gallery n



If the walls are made of beton (or other building materials) upon the rocks the quantity of radon exhaled from the walls in the gallery depends mainly on the physical properties and the radioactivity content of soil and building materials (tables 2-1 and 2-2) and secondarily on the term $F_{g,n}$, that is also a function of the exhalation rates from the other walls and the radon concentrations inside the galleries, as it can be deduced considering the diffusion equations and applying the boundary conditions at the interfaces. All these equations are therefore coupled. Taking into account the physical constitution of building materials, the type of soil and the quantity of water gushing out from the walls iterative procedures [8] can be applied in order to calculate radon concentrations inside galleries. Results of this calculations show that soil and building materials are the main sources of radon only when water exhalation rates are low.

7. Conclusion

During excavation works for the construction of an hydroelectric power plant in the north of Italy monitoring surveys of radon and gamma radiation were carried out in compliance with the requests of local authorities. Good reproducibility and accuracy of instantaneous and very short term time averaged measurements were achieved. Acceptable radon concentrations were found when ventilation was properly set. The main entry gate was motorized and, using correlation data between radon concentration and airflow velocity in the entry gallery, the ventilation system of the power station was automated in order to properly regulate the speed of the main fans. Mathematical models were implemented in order to calculate radon concentration inside galleries. Results of these calculations show the effectiveness of iterative techniques.

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