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Radon in Caves

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Abstract:

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The physical characteristics of radon are reported as well as its sources,the transport in rock and its behaviour in caves. Then, the instruments,both active and passive, used for the measurement of radon concentration are discussed by taking into account their respective advantages and disadvantages for the use in the cave environment. Since in many countries radon is the object of regulations that were adopted for radiation protection purposes, this aspect is examined and the recommendations issued by international organisations and enforced in different countries are reported. Materials, methods and other remarks on the limits implementation are also listed with the aim of providing the managers of show caves with some instruments to comply with the domestic requirements with the most convenient solution.

Keywords: radon, cave environment, radiation protection, monitoring, regulations.

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FOREWORD

Radon in caves has been studied since many years and a good amount of knowledge on the behaviour of this gas in caves is available. It is well known that radon, as well as carbon dioxide, may be used as a tracer to investigate the cave climate with particular reference to air circulation.

In many countries, radon is the object of regulations that were adopted for radiation protection purposes. In fact, there is convincing evidence of excess lung cancer documented in underground mining studies, and all present risk estimates for radon and decay products exposure are based on the mine exposures (Doll, 1992).

On account of these results, many recommendations, regulations and laws concerning a system of constraints to radon concentration indoor were issued, notwithstanding that the risk in homes is not well defined because the exposure conditions are different. The sources of radon indoor are the soil underneath and the building material. The investigations carried out frequently revealed a higher radon concentration in cellars and basements.

Such results, together with a number of studies performed in caves, called the attention on this peculiar environment. For this reason, caves, tunnels and underground spaces are often explicitly quoted in recommendations and regulations. The health effects due to radon inhalation are evaluated according the so-called "Linear No Threshold" (LNT) relationship. This means that radiation effects produced with low level irradiation can be predicted quantitatively by linear extrapolation from effects produced with high level irradiation; and any amount of radiation, however small, is potentially harmful.

The LNT hypothesis provided a reasonable conservative approach to risk assessment for the purpose of standard setting. However, this hypothesis may lead to unnecessary conservative radiation protection standards, particularly for low level irradiation. In particular, it must be stressed that there is insufficient evidence to support the use of LNT hypothesis in the projection of the health effects of low-level radiation. Therefore, the risks of lung cancer attributed to radon are simple extrapolations not scientifically found.

Anyway some organisations, such as, the US Environmental Protection Agency or the US National Academy of Sciences, stress the reduction of radon risk in homes. Recently the Environmental Protection Agency (US-EPA, 2003) issued a report estimating the excess cancer in a population due to radon exposures.

The residential exposure rates are roughly an order of magnitude lower than that experienced by miners, from whom residential risk estimates are derived. With reference to the health effects due to radon exposure, Tommasino (1995) reported that, the analogy between working age males labouring in mines with families sleeping in their bedrooms may not be perfect. However, even though the risks of exposure to radon and its decay products in dwellings are not well characterised, yet their potential lung cancer risks need to be strongly addressed, both in homes and occupational environments.

The death-risk from a life-time exposure to average indoor concentration is estimated to be in the range of 0.1 to 1%, depending on the country and the smoking habits. These risks are of the same order of magnitude of risk of dying in a fall at home or a home fire. Moreover, houses having several times the average radon concentration have radon risks, which can equal or exceed the 2% risk of death in an automobile accident.

Notwithstanding these still open questions, what reported above couldn't be regarded as an invitation to ignore the principles of radiation protection when the problem of radon in caves is considered. But, it is necessary to comply with the levels indicated by the regulation also if such levels may be questioned on a sound scientific basis. In fact, the domestic epidemiological studies, to date, do not show a statistically significant excess risk.

With reference to radon dosimetry, its intrinsic difficulty must be stressed. In fact, the relationships between the estimated dose and effects reported by different studies are often not comparable. Then the International Commission on Radiological Protection (ICRP 1993; 1994) recommended some assumptions and dose conversion conventions to assure more uniform calculations. Anyway, any parameter influencing the dosimetry (decay products equilibria, attached and unattached fraction, etc.) varies in a rather wide range. Recently Vaupotic & Kobal (2004), have emphasised the role played by the unattached fraction of radon decay products for radon dosimetry.

By taking into account both the errors associated in the measurements and the spread of the parameters quoted above, it was assumed that a more refined procedure for the evaluation of the dose delivered by radon and its decay products to people would have introduced an unnecessary complication.

Therefore, throughout this article, the current recommendation by the ICRP are adopted without any further refinement. More accurate studies are considered to be important but are outside the scope of this paper. Rather, it is a huge database of various works reported in different papers.

In addition, the article also provides some information on the most suitable techniques and procedures to be preferred in cave monitoring in order to avoid poor (but expensive!) services, which may be offered by someone who is not aware of the very special characteristics of the cave environment.

NOTE

The information more interesting for cave managers is included under DETECTORS and MANAGEMENT

INTRODUCTION

The problem of radon has drawn the attention of many scientists all over the world, particularly in the last decade. The main research goal has been the evaluation of the indoor radon concentration essentially because the most relevant source of the population exposure is radon.

Nevertheless caves have been of interest because the radon concentration in these environments may sometimes reach high values. A rather large number of investigations has been carried out all over the world, from the point of view of both research on radon behaviour in a cave environment and radiation protection. Since the early studies, the material and methods adopted have changed extensively and at the same time more attention has been given to the role of radon in the total dose delivered to people. Sometimes the fear of the consequences to radon exposure has been emphasised too much.

The concentration of thoron in caves is typically in the range of 5 to 15% of the radon values, i.e. within the error that normally affects radon measurements. For this reason and in order to simplify the whole problem, only radon is taken into account in this article.

Limits to the concentration of radon and its decay products both at work and at home are recommended or established by law. In general, the remediation actions to comply with these limits indoors, consist of sealing the ways of propagation of radon and enhanced ventilation. Obviously, both solutions cannot be applied to caves because any intervention on the cave atmosphere would imply the destruction of natural equilibria.

Therefore, when a research or monitoring network has to be initiated in a cave, it is necessary to assemble most of the essential issues to be taken into account along with the measures to be taken in order to comply with the existing regulation. Care should also be taken not to cause any inconvenience to the cave environment.

It is interesting to report here a case of "natural air conditioning" obtained a century ago at Luray Caverns, Virginia, USA (Hunner, 1901). The air from the cave (at about 12° C) was extracted by a fan and supplied to a sanatorium where the air was practically free of bacteria (Claudy, 1908). Obviously such a procedure would not be admitted nowadays from the point of view both of radiation protection and cave climate equilibrium (Gurnee, 1977).

RADON

Physical characteristics

Radon is a radioactive noble gas. Compared to the other noble gases, it is the heaviest and may form some compounds as clathrates and complex fluorides; in particular it forms a metastable clathrate-hydrate with water; Rn-6H_2O (Martinelli, 1993). Radon has many isotopes, but only three of them are naturally occurring. In Table 1 their radioactive properties are reported.

Table 1 - Radioactive properties of natural radon isotopes.

Isotope	From:	To:	Half life	α Radiations
^{219}Rn	^{223}Ra ^{219}At	^{215}Po	3.9 sec	6.82(82%);6.55 (13 %)MeV
^{220}Rn	^{224}Ra	^{216}Po	54 sec	6.28 MeV

These radionuclides belong to natural radioactive decay series:

^{220}Rn to the Thorium series (with mass number which are multiples of 4)
^{222}Rn to the Uranium series (with mass number which are multiples of 4+2)
^{219}Rn to the Actinium series (with mass number which are multiples of 4+3)

The Neptunium series (with mass number which are multiples of 4+1) does not occur in nature because the half-life of its longest-lived member is three orders of magnitude shorter than the age of the universe. But, in practice, only ^{220}Rn and ^{222}Rn may be relevant from the point of view of radiation protection, because the Actinium series derives from ^{235}U, which is only the 0.72% of natural uranium, and ^{219}Rn has a half-life of 3.9 seconds. Therefore, this isotope cannot play any relevant role. It must be pointed out that also in presence of high concentration of ^{235}U, as it may occur with highly enriched uranium (HEU), ^{219}Rn cannot escape into the environment for its very short half-life. Since ^{222}Rn has a half-life of 3.8235 days, it can be released from the rock where it has been generated, contrarily to ^{220}Rn whose short half-life limits the distance it can travel before decay.

In consequence, the amount of ^{220}Rn entering the environment is less than the amount of ^{222}Rn, and ^{220}Rn and its decay products are usually neglected, although their contribution is not as trivial as that from ^{219}Rn. The decay chain (with only the most common branches included) of ^{222}Rn is reported in Table 2.

Radon is moderately soluble in water and has a high solubility in organic liquids, with the exception of glycerine that holds a lower solubility than in water. It is readily absorbed on charcoal and silicon gel. In a multiphase system, at normal environmental temperature, radon concentrations are greatest, intermediate and least in the organic liquid, gas and water phases respectively. If temperature is increased, the concentration in the gas phase increases at the expense of the liquid phase. These properties have been successfully exploited for the determination of radon and its extraction from other gases and liquids (Tommasino, 1995).

Some chemical-physical properties of radon are reported in Table 3.

Table 2 - Radioactive decay chain of ^{222}Rn (simplified).

Radionuclide	Half-life	Principal radiations and energies (MeV)
^{222}Rn	3.8235 d	100%)
^{218}Po	3.11 min	100%)
^{214}Pb	26.8 min	--
^{214}Bi	19.8 min	539 (18%), 0.567 (3%), 0.667 (1%), 0.683(7.5%), 1.27 (18%)
^{214}Po	$1.6*10^{-4}$ s	100%)
^{210}Pb	22.3 y	--
^{210}Bi	5.012 d	(100%)
^{210}Po	138.38 d	(100%)
^{206}Pb	stable	--

Table 3 - Chemical-physical properties of radon (Natl. Council on Radiation Protection and Measurements, NCRP 1988).

Property	Value
Boiling point (normal pressure)	- 61.8 °C
Density (normal temperature and pressure)	9.96 kg/m^3
Coefficient of solubility in water at atmospheric pressure, at the temperature of:	
0 °C	0.57
20 °C	0.250
37 °C	0.167
100° C	0.106
Coefficient of solubility at atmospheric pressure and temperature of 18°C in:	
Hexane	16.56
Olive Oil	29.00
Petroleum (liquid paraffin)	9.20
Toluene	13.24

Sources

^{238}U decays through several steps into ^{226}Ra, which decays into ^{222}Rn. Therefore, the concentration of ^{222}Rn depends upon the concentration of these radionuclides in the rock, which varies in a very large range. But ^{222}Rn is a gas and must get out from the mineral lattice or from the molecule in which it is formed.

When ^{226}Ra disintegrates a ^{222}Rn atom and an alpha particle are formed. The alpha particle is ejected and the ^{222}Rn atom is subjected to a recoil effect that dislodges the atom from the mineral lattice or molecule where ^{226}Ra disintegrated. The distance the ^{222}Rn atom can move ranges between 0.02 to 0.07 μm in a mineral grain according to the density and by this movement, the atom emanates from the mineral.

Obviously ^{222}Rn can be ejected form the mineral grain only if it is very close to the surface and the recoil was in an outward direction. Recently Deszö et al. (2002) carried out some measurements of the radon exhalation from clay and limestone, respectively, in Baradla Cave (Hungary). They found that under normal cave climatic conditions, the effective diffusion length of radon in clay is large enough to play a significant role in feeding the cave atmosphere with radon gas. From laboratory gamma spectroscopy measurements the ^{226}Ra content of clay samples found to be typically about 20-40 higher than in limestone samples (Hakl, 2004). From clay, about 44% of the radon could be released into the atmosphere, while from limestone only 2.5% could be released. By the combination both of the ^{226}Ra concentration and the release rate, the contribution of limestone was about two orders of magnitude less than the contribution of clay. Therefore it can be assumed that in general clay is the major radon source.

In water, the ^{222}Rn range due to the recoil effect is 0.1 μm and in air 63 μm. Once the ^{222}Rn is in one of these fluids, it is subjected to diffusion and transport, which are described in the next chapter.

Transport in rock

Both diffusion and transport by moving fluids play an important role in radon movement in the ground. In general, diffusion is the dominant mechanism in the intergranular channels, capillaries and smaller pores; while in the larger pores and fractures, transport may become important or even dominant (Tanner, 1978).

The heterogeneity of the geological material is a source of large variation of the radon diffusion in a porous medium, with respect to the theoretical assumptions. E.g. mica and vermiculite, which are flaky minerals, have a shape factor that causes the diffusion coefficient to be one-half to one-third the theoretical value. Clay and shales contains significant proportions of flaky minerals, usually oriented so as to impede vertical movement. They retard diffusion to a greater extent than a porous medium having the same porosity but consisting of spherical particles.

The fraction of the radon which escapes directly from soil depends upon the depth at which it is formed and the permeability of the ground. According to NCRP (1984), about 10% of the radon formed in the top metre of soil reaches the atmosphere.

In Table 4 experimental diffusion coefficients for some rocks and other materials are reported.

Table 4 - Experimental diffusion coefficient for some rocks and other materials.

Material	Diffusion coefficient (cm^2/s)	Reference
Muscovite chlorite schist	$1.436*10^{-5}$	Gosh & Sheikh, 1976
Epidiorite	$1.15*10^{-6}$	Gosh & Sheikh, 1976
Quartzite	$0.79*10^{-6}$	Gosh & Sheikh, 1976
Soil, Nevada Test Site	$0.36*10^{-1}$	Schroeder et al., 1965
Air	$0.12*10^{-1}$	Hirst & Harrison, 1939
Paraffin	$1.3*10^{-6}$	Porstendörfer, 1968
Polystyrene foam	$5.7*10^{-4}$	Porstendörfer, 1968

But the main factor influencing the radon flux in rock is its transport by groundwater through joints and faults. The migration through fractures or vents to underground cavities is not amenable to general mathematical analysis because the open-space is unique at each location.

High surface concentration of ^{222}Rn in soil has long been associated with buried faults or dislocations, and it was possible to locate faults overlaid by thin sediments. Sometimes uranium and ^{226}Ra migration from faults and accumulation by means of ion exchange with clay in the soil are the principal cause of ^{222}Rn anomalies over the faults.

Radon decay products.

As it was reported in Table 2, ^{222}Rn decays into Pb, Bi and Po isotopes, which have a short half-life. In Table 5, the approximate time to equilibrate radon decay products with ^{222}Rn are reported. Full equilibrium is attained in 4 hours.

Table 5 - Approximate time to equilibrate radon decay products with ^{222}Rn (Evans, 1969).

Decay product	Half-life	Time (min) to indicated equilibrium			
		25%	50%	90%	99%
^{218}Po	3 min	1	3	10	20
^{214}Pb	27 min	16	31	95	180
^{214}Bi	20 min	36	60	135	230
^{214}Po	$1.6*10^{-4}$ s	36	60	135	230

These decay products are solid and they attach to any surface that they come in contact as well as to the small particles, which are normally present in air. The abundance of these particles ranges from about 10^{-3} cm^{-3} in clean air to about 10^5 cm^{-3} in urban areas (Junge, 1963). The result of this process is that a full equilibrium between decay products and radon gas is rarely attained in the atmosphere.

The equilibrium factor, F, has been widely studied in different conditions to evaluate the dose to persons exposed to a given concentration of ^{222}Rn when equilibrium conditions with its decay products are not attained. In usual indoor situations, the equilibrium is a function of the air exchange rates in particular. According to a study carried out by Swedjemark (1983) the mean value of F ranged between 0.51 for low exchange rates to 0.33 for high exchange rates. Often a value of 0.4 or 0.5 is assumed for current dose evaluations.

Behaviour in caves

Hakl, Hunyadi and Várhegyi (1997), summarising a large number of data collected during the last decades published a very extensive paper on radon monitoring in caves. The role of radon as a natural tracer to study the transport processes at the interfaces of lithosphere, hydrosphere and atmosphere is fundamental. It may provide a large amount of information on the development and changes of cave microclimate.

In a cave the air is in general rather clean, i.e. there are less small particles than outdoors or in urban areas.

In Table 6, some values of the equilibrium factor measured in caves are reported. The lower values were found in places close to the tourist trails where persons are a relevant source of small particles as lint, which is also a form of pollution of the cave environment.

During a survey performed in the most important Italian show cave the "Grotta Grande del Vento" (Marche, Ancona) more commonly known as "Grotte di Frasassi", a series of measurements of ^{222}Rn and its decay products concentrations were made in a stop area of the visitors along the tourist trail. The results are reported in Fig. 1.

In the afternoon, the value of F increased until the last visit to the cave, around 20:00, which lowered it to 0.7 followed by a recovery to higher values during the night, when only the persons engaged in the measurements were inside the cave. The influence of visitors on the value of F is quite evident, particularly in a clean environment such as a cave where the concentration of small particles in the atmosphere is normally very low.

The average of the equilibrium factor F as reported in Table 6, weighted over the number of measurements (which are more than 880) was calculated to be 0.57. On account of the cave atmosphere, which is particularly clean in comparison to the indoor atmosphere, this value, which is higher than the value currently adopted for indoor evaluation (see above), can be used for caves when a specific evaluation is not available.

Table 6 - Some values of the equilibrium factor measured in caves.

Cave	Equilibrium factor	No. of measurements	Reference
Gellért-hill System, Budapest, Hungary	0.94	9	Virág & Urbán, 1970
Idem, Aragonite cave	0.73	4	Virág & Urbán, 1970
Carlsbad Caverns, NM, USA, Main Cave	0.44	30	Yarborough et al., 1978
Idem, Main cave	0.59	4	Ahlstrand & Fry, 1978
Idem, Lower cave	0.50	3	Yarborough et al., 1978
Idem, New Cave	0.90	3	Yarborough et al., 1978
Idem, Pump Room Cave	0.56	78	Ahlstrand & Fry, 1978
Crystal Cave, Sequoia, Calif., USA	0.90	4	Yarborough et al., 1978
Jewel Cave, SD, USA, Historic Tour	0.19	2	Yarborough et al., 1978
Idem, Scenic Tour	0.81	14	Yarborough et al., 1978
Lehman Cave, Nevada, USA	0.64	70	Yarborough et al., 1978
Mammoth Cave, Kentucky, USA	0.81	22	Yarborough et al., 1978
Oregon Cave, Oregon, USA	0.66	6	Yarborough et al., 1978
Round Spring Cave, Ozark, MO, USA	0.98	6	Yarborough et al., 1978
Wind Cave, SD, USA	0.46	10	Yarborough et al., 1978
Howe Caverns, NY, USA	0.67	9	Seymore et al., 1980
Grotta Grande Vento, Marche, Italy	0.69	4	Cigna & Clemente, 1981
Idem Sala dei Duecento	0.85	7	Clemente, 1980
Katerinska Cave, Moravia, Czech Republic	0.75	25	Burian & Stelcl, 1990
Punkvevni Caves, Moravia, Czech Republic	0.86	33	Burian & Stelcl, 1990
Sloupsko-sosuvske Caves, Moravia, CzechRep.	0.87	50	Burian & Stelcl, 1990
Balcarka Cave, Moravia, Czech Republic	1.94	20	Burian & Stelcl, 1990
Grotta di Quinzano, Verona, Italy	0.55	5	Trotti et al., 1993
Szemlö Hill Cave, Budapest, Hungary	0,50	31	Szerbin, 1996
Pál Valley Cave, Budapest, Hungary	0.48	61	Szerbin, 1996
Therapeutic Cave, Tapolca, Hungary	0,51	26	Szerbin, 1996
Vass Imre Cave, Northern Hills, Hungary	0.53	24	Szerbin, 1996
Akiyoshi-do Cave, Yamaguchi, Japan	0.70	4	Iimoto, 2000
Taisyo-do Cave, Yamaguchi, Japan	0.71	4	Iimoto, 2000
Kagejiyo-do Cave, Yamaguchi, Japan	0.52	3	Iimoto, 2000
Postojna Cave, Railway Station, Slovenia	0.56	200	Vaupotic et.al., 2001
Idem, Lowest Point, Slovenia	0.54	200	Vaupotic et.al., 2001
Therapeutic Cave, Tapolca, Hungary	0.57	41	Kávási et al., 2003

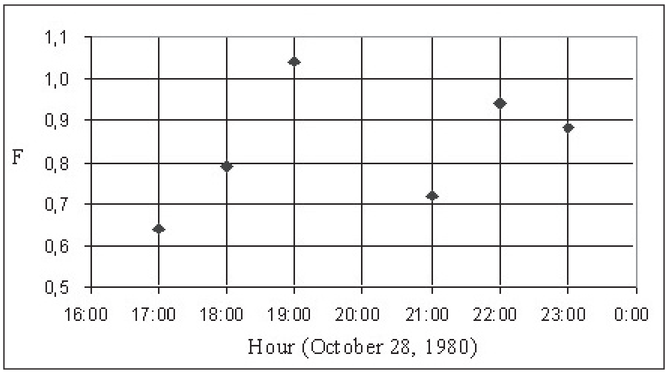

Fig. 1 - Equilibrium factor F measured at “Sala dei Duecento” in Grotta Grande del Vento (Italy) on October 28, 1980 (Clemente, 1980).

Radon concentration in cave air is influenced by a wide number of factors, as radium concentration in the rock, porosity, air and water flow, atmospheric pressure, earthquakes, etc. But, in general, a seasonal fluctuation is found with a maximum in summer and a minimum in winter. A typical example is reported in Fig. 2 for a time interval of 18 years (Hakl et al., 1995).

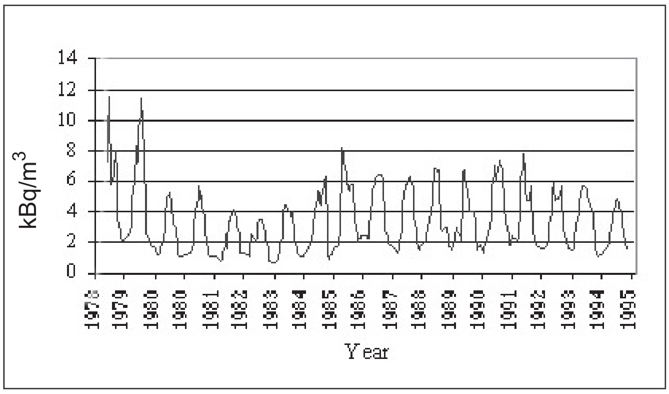

Fig. 2 - Radon concentration in Hajnóczy Cave (Hungary) (Hakl et al., 1995).

This rather long series of measurements shows that, in addition to the seasonal fluctuation, other irregular variations of the radon concentration also exist, which cannot be clearly correlated with other environmental parameters do exist.

THE DISTRIBUTION OF RADON CONCENTRATION IN CAVES

With reference to the distribution of the average values of radon concentration in caves, they are spread over a very wide range of values as shown by Hakl et al. (1995) who collected 303 data from 220 different caves. For this fact the number data is still too poor for an exhaustive analysis, particularly for high values.

Such data, as kindly supplied by Hakl (2004), were already the object of a short note (Cigna, 2003) in which the distribution of values of the radon concentrations were considered as a power law, typical of many distributions of this kind.

But the number of caves with a radon concentration within a given interval was plotted in function of these intervals instead of the number of caves with a concentration above a given value in function of such values (Curl, 2005). Therefore the obtained "fractal" dimension of the radon concentration distribution (D = 1.26) was not correct and I apologise for this error.

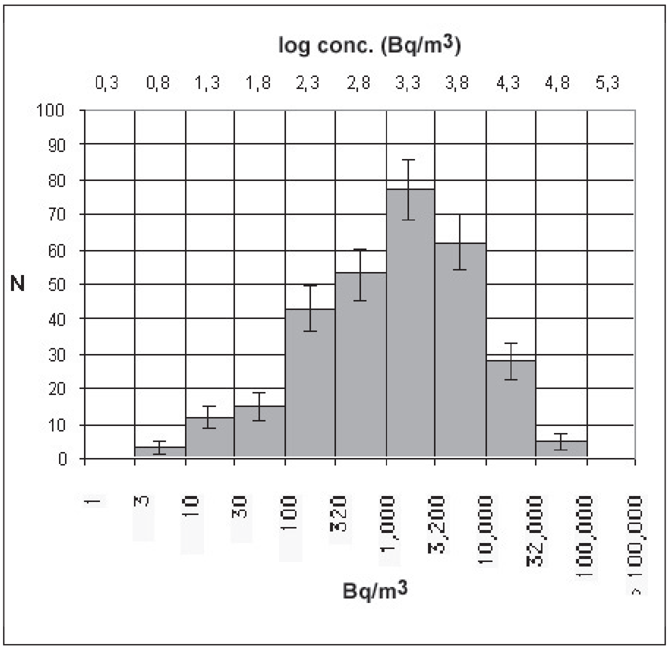

Fig. 3- The log normal distribution of 303 average radon concentrations from 220 caves from all over the world. (original data from Hakl, 2004).

However it is possible to investigate if other kinds of distribution might be adequate. The log normal distribution is a continuous distribution in which the logarithm of a variable has a normal distribution. A log normal distribution results if the variable is the product of a large number of independent, identically distributed variables in the same way that a normal distribution results if the variable is the sum of a large number of independent, identically-distributed variables. Log normal distributions of geological features, as fractures, are found frequently.

Since this is the case of radon concentration in caves, the lognormal distribution of the Hackl's data was calculated. The result, as reported in Fig. 3, shows an average value around a concentration of about 2500 Bq/m^3, but the shape of this roughly gaussian distribution is not symmetric suggesting that there are different mechanism of radon diffusion in caves. In particular probably two "families" of processes might take place

for the values respectively below and above such an average.

In addition, since radon transport is influenced, among other factors, by fractures' size, also the distribution of such sizes plays a role in radon concentration in caves.

Obviously a more correct investigation on the distribution of radon concentration in caves should take into account the multiple measurements from individual caves and use an average value in such cases. .

At present, according the data available, it is only possible to describe the distribution of ^{222}Rn concentration in caves as reported above and list some points that deserve much interesting aspects to be investigated in future researches.

In particular for rather low values, it is evident the effect of the geochemical characteristics of the rock (limestone in particular) in which it is difficult to have very low concentrations of ^{226}Ra. Then, when the transport mechanisms of radon are considered, another factor should be taken into account as the air and water flow. Finally the source of radon in a given cave should be ascertained, if it were in the bulk of the limestone or in other rocks connected to the limestone though fissures.

DETECTORS

Since the middle of the 70's the role of radon in delivering about one half of the dose due to the natural background became quite evident. Consequently, many methods to measure radon and its progeny concentration were developed. George (1996) published an extensive review of the state-of-the-art. Anyway, due to continuous technological development, a regular update of the costs and models is essential.

A short description of the different measurement techniques is reported here.

Active instruments

These instruments require power for operation. Sometimes they contain a small battery, which provides backup power in the event of a power outage during operation. The methods of measurement are ionisation chamber, scintillation cell or solid-state detectors.

A continuous sampling is used for the study of the time dependence of radon concentration. An average concentration value for adjustable time intervals is stored and such results may be downloaded into a computer at convenient intervals.

Such instruments are useful to obtain an indication of the local concentration of radon, prior to a long-term evaluation as required by regulations (Fig. 4).

Fig. 4 - A continuous monitoring instrument in the Bossea Cave (Italy).

Passive instruments

These instruments, which do not require power for operation, are suitable for evaluating short- and long-term measurements, i.e. determination of radon concentration averaged over a period of a few days to a year. Such devices can be divided into two main categories: the diffusion and the permeation samplers.

A diffusion sampler consists of a tube with a detector located at one end of the diffusion zone formed by the tube, while the other end is open to the atmosphere to be monitored. If the length of the tube is greater than 30 cm the thoron decays before it reaches the sensitive volume of the detector and therefore radon concentration only is measured.

A permeation sampler assures a more efficient way to eliminate the thoron and water vapour, by using a polymeric membrane (namely a polyethylene film a few tens of a μm thick) in which radon must first dissolve and then diffuse. In particular a permeation sampler can be simply formed by a heat-sealed plastic bag made of polyethylene containing the detectors.

• *Activated charcoal detectors*

A canister containing some activated charcoal absorbing radon from the atmosphere is used often for screening purposes. It has been pointed out by Tommasino (1995) that, these detectors are sufficiently sensitive for the assessment of short-term integrated (less than one week) radon exposure. Because of the short half-life of radon, the exposure period cannot be longer than one week and the detector must be analysed in the laboratory by γ-ray spectrometry soon after exposure. In particular, it must be stressed that this method does not provide a true integration, but a response more closely related to the last day or two of exposure.

Furthermore, the activated-charcoal has a response, which is highly dependent on temperature and humidity (Ronca-Battista & Gray, 1988). In particular, humidity reduces the absorption of radon by the charcoal. For these reasons such detectors are not suitable for use in caves unless protected by a polyethylene bag.

• *Electret ionisation chambers*

The first measurements of radionuclides carried out about a century ago by Madame Curie and Rutherford, used a primitive total ionisation chamber as an electroscope. In the second half of last century the so-called pen-dosimeters were widely used (and sometimes still in use). They consist in an electroscope with a hairline indicator viewed through a simple microscope. The electroscope is connected to an ionisation chamber and it is charged by means of its charger until is zeroed. The ionisation chamber discharges the electroscope and the dose measured by the device can be read directly.

Pen-dosimeters are not suitable for radon measurement because radon cannot reach their ionisation chamber. On the contrary, the electret ionisation chamber is a monitor consisting of a very stable electret mounted inside a small chamber made of electrically conducting plastic. The electret is a Teflon disk, which has been electrically charged and stabilised by appropriate processes. It serves as both a source of the electrostatic field and as a sensor. Radon gas passively diffuses into the chamber through filtered inlets, and the alpha particles emitted by the decay process ionise air molecules. Ions produced inside the chamber are collected onto the electret, causing a reduction of its surface charge. The loss of charge is measured by an electrostatic voltmeter and related to radon exposure through a calibration process. Also these detectors must be protected by a polyethylene bag to avoid a discharge due to humidity.

Since the chamber also responds to gamma radiation, the gamma exposure must be subtracted in order to assess the radon exposure alone.

• *Etched track detectors*

This method was originally developed for detecting heavy charged particles (Fleischer et al., 1965) and subsequently used for radon measurements. It is based on the fact that an α-particle leaves a latent track of damage in dielectric media. Later the latent track can be etched with a suitable etchant (e.g. NaOH), by enlarging them sufficiently to become visible under an optical microscope. The number of tracks is obviously proportional to the concentration of radon and/or radon progeny and the time of exposure.

Fig. 5 - An etched track detector in place (Grotte di Toirano, Italy).

Initially the tracks were counted optically, but in 1970 an automatic system was developed by Cross and Tommasino (1970) with the spark counter. The film with the etched-through holes is placed in a capacitor. The top electrode is a metallized film (typically aluminised Mylar) and the other electrode is solid metal. When a dc voltage is applied to the capacitor, the etched tracks begin to breakdown sequentially. But each spark vaporises a hole in the aluminium, effectively removing the conductor layer on one side and is easily counted.

The advantage of etched track detectors is evident, since the dielectric media respond to only alpha particles and therefore these detectors are quite selective for radon and its progeny. The materials typically used for detection of radon and its progeny are made of cellulose nitrate (LR 115, CN 85), bisphenol-A polycarbonate (Lexan, Makrofol), and polyallyl diglycol carbonate (PADC). The PADC, also known as CR-39, is by far the most sensitive material, which is capable of recording alpha particles with a wide range of energies (Tommasino, 1997). In Fig. 5 a detector of this kind is reported.

• *Polyethylene*

This method can be used for radon measurement in water (Tommasino 1998). By placing polyethylene foils in water, because of its relatively high solubility, polyethylene absorbs radon, which can then be measured by gamma spectrometry at the end of the exposure. This method has the advantage of integrating radon concentrations over time and water volume, because the long-lived decay product, ^{210}Pb, remains implanted in polyethylene.

The very low cost and simplicity make such a method particularly attractive, once a suitable calibration is established to calculate the ratio between the concentrations in water and polyethylene respectively.

MEASUREMENTS

The measurement of radon concentration for radiation protection purposes involves some problems because radon has a short-lived progeny with totally different physical-chemical properties. In fact radon is a noble gas while its decay products are solid (metallic ions) which attach to any small particle normally present in air as well as any other surface. For this reason the equilibrium, i.e. when the activity of each decay product equals that of the parent radon, is rarely attained. Some values of the equilibrium factor for different situations were reported in the previous section.

The processes influencing the concentration of radon progeny in the air are attachment to atmospheric aerosols, plate-out (surfaces), recoil from aerosols and surfaces, and decay. Ionisation, electrostatic forces, gravity, airflow, and steady-state molecular diffusion influence the deposition on surfaces. If the less important parameters are neglected and a diffusion coefficient in air equal to 0.06 cm^2s^{-1} is assumed for ^{222}Rn, ^{218}Po and ^{214}Po a reduced concentration of radon decay products near the surfaces can be calculated. Their concentrations significantly decrease at distances less than about 10 cm from the walls and at a distance above 50 cm the influence of plate-out can be neglected (Ilic & Sutej, 1997).

Units

On the problems concerning directly the measurements of radon and its decay products described above, different assumptions were made to simplify such measurements for current radiation protection purposes.

In fact, the measurement of the respective concentrations of the short-lived radon decay products faces practical difficulties and is rarely attempted.

The counting of alpha particles is the easiest solution, which can be carried out with simple equipment.

Thus, the potential alpha energy concentration was defined as the concentration of short-lived radon progeny in air in terms of the alpha energy released under complete decay through ^{214}Po. Consequently, the potential alpha energy exposure of an individual can be calculated by the time integral of the potential alpha energy concentration over a given time period.

The potential alpha energy exposure is often expressed in the historical unit Working Level Month (WLM). One WL is defined as a concentration of the potential alpha energy of $1.300*10^8$ MeV V m^{-3}, corresponding to a concentration of the radon progeny in equilibrium with 100 pCi l^{-1} (3700 Bq l^{-1}). Since the quantity was introduced for specifying occupational exposure, 1 month was taken to be 170 hours (ICRP 1993), an occupancy of 2000 hours per year at work and 7000 hours indoors (UNSCEAR, 1988).

The potential alpha energy concentration (expressed in J m^{-3} or MeV m^{-3}) of any mixture of radon progeny in air can also be expressed in terms of the so-called equilibrium equivalent concentration, EEC, of their parent nuclide, radon. The equilibrium equivalent concentration (expressed in Bq m^{-3} or pCi m^3), corresponding to a non-equilibrium mixture of radon progeny in air, is the activity concentration of radon in radioactive equilibrium with its short-lived progeny that has the same potential alpha energy concentration as the actual non-equilibrium mixture (ICRP 1993).

The EEC depends only on the concentrations of the short-lived progeny, as only this is considered radiobiologically important.

When the concentrations of the decay products, namely ^{218}Po, ^{214}Po and ^{214}Bi are known, the EEC is given by the following equation (Planinic & Faj, 1989):

$$EEC = 0.1046*C_{218Po} +0.5159*C_{214Po} +0.3795*C_{214Bi}$$

the constants being the fractional contributions of each decay product to the total potential alpha activity from the decay of unit activity of radon.

In Table 7, some equivalencies between historical units and the current SI units are reported.

Table 7 - Conversion coefficients between historical and SI units.

From	To
1 pCi	0.037 Bq
1 Bq	27 pCi
1 J m^{-3}	$6.424*10^{12}$ MeV m^{-3}
1 MeV	$1.602*10^{-13}$ J
1 Sv	200 WLM
1 WLM	5 mSv
1 WLM	3.54 mJ h m^{-3}
1 mJ h m^{-3}	0.282 WLM (F=1)
1 WLM	$6.37*10^5$ Bq h m^{-3} (F=1)
1 Bq h m^{-3}	$1.57*10^{-6}$ WLM (F=1)
100 pCi L^{-1}	1 WL (F=1)
100 pCi L^{-1}	0.5 WL (F=0.5)

Monitoring network

A monitoring network can use either active or passive instruments. Active instruments can be adjusted to record radon concentrations at fixed intervals and stored into a data logger to be downloaded according to a convenient schedule. For research purposes the intervals depend on the scope of the research and therefore may vary within a very wide range. When the monitoring is set up to comply with the local regulations, two measurements per day (e.g. noon and midnight) could be established because in this way also the diurnal cycle would be taken into account.

If an environmental automatic monitoring network for climatic parameters is available, as presently suggested for any show cave, then also the output of the radon instrument could be included among the other parameters. In any case this is not strictly necessary because radon concentration is purely due to natural sources. Therefore, a download every month or also at longer interval is acceptable.

On the other hand, passive detectors are surely less expensive and have also the advantage of integrating the radon concentration over the whole time interval of operation. Among the different kinds of detectors, as described previously, the track etched detectors are the most suitable for use in caves because they are not affected by humidity.

In general, it is convenient to apply to some organisation, which provides the detectors, processes them at the end of the exposure time, and releases the result. In order to comply with regulations such results must be certified and the organisation taking care of the measurements must have reliable calibrations.

RADIATION PROTECTION

History

The first report of an effect attributable to ionizing radiations, and particularly to radon in mines, is due to Epicurus, a Greek philosopher (born in 341 B.C. in Samos, died in 270 B.C. in Athens) whose works survived only partially to the present. The main part of his works is known through a number of charred papyri found in a library of Hercolanum damaged by the eruption of 79 A.D. but no data concerning the effect of ionizing radiations could be found.

Such data are reported by Titus Lucretius Carus, a Latin poet, who was born around 95 B.C. (perhaps in Pompei, near Naples) and committed suicide about 44 years later after a love potion drove him mad. He wrote a poem entitled *"De rerum natura"* (= about the nature of things) which is quite peculiar because it gives an exceptional view on the scientific knowledge at that time (Carus, 61±10 B.C.).

Therefore, T.L. Carus' reference to a miner's disease is probably the oldest record of radiogenic lung cancer (which happens to be the oldest type of radiation-induced malignancy known) because he quotes a work written by Epicurus about 200 years earlier.

It is difficult to know for certain if the disease was caused by silicosis or radon: nevertheless it must be pointed out that in the vicinity of Mt. Pangaion (where are the mines quoted by T.L. Carus) the indoor radon concentration is above 100 Bq/m^3 and the outdoor gamma-ray dose is around 100 nGy/hour (Green et al., 1991). Therefore, these values (among the highest of the whole Greece) support the hypothesis that, in such mines, radon concentrations high enough to induce malignancies in local miners could be found. On the other hand, the mining technology of that time would have hardly produced large amounts of dust to cause frequently silicosis.

One century later, another Latin philosopher, Lucius Annaeus Seneca (born on 4 in Córdoba, Spain, died on 65 A.D. in Rome) /reported again the problem of noxious gases released in caves which sometimes could perhaps have some connection with the radon (Seneca, 60±5).

In the same period another Latin writer, Caius Plinius Secundus, known as "Plinius he Elder" (born on 23 in Como, died on 79 A.D. in Stabia) produced a large encyclopaedia (Plinius, 77) divided in 37 volumes. He was surely aware of the news reported by previous authors and some reference to noxious releases from the soil is included in his work but no specific data useful for our purpose can be found.

The next report of radiogenic lung cancer occurs much later. In fact Agricola recorded it in the 16th century. The first quotation in "Bermannus" (Agricola, 1530) was expanded later (Agricola, 1556): "Of the illnesses, some affect the joints, others attack the lungs, some the eyes, and finally some are fatal to men". Also Paracelsus reported an unusually high mortality from lung disease occurring in younger miners. He had written his book in 1537 but it was printed only after his death (Paracelsus, 1567). Successively also B. Ramazzini (1713) quoted some previous scientists emphasizing both Agricola and Lucretius remarks.

Among the miners in the Schneeberger-Jachymov region in Erzgebirge the disease was known as the "Schneeberger Krankheit" and it was diagnosed as lung cancer in 1879 (Härting & Hesse). Its possible association with radon was suggested about 40 years later when the high radon levels in mines of that region were discovered and the real cause of this disease was recognized in the 1950s only when the first attempts of lung dosimetry were made (Aurand et al., 1955; Bale & Shapiro, 1955).

Recommendations

The important contribution of radon and its decay products to the natural radiation background called attention to the convenience of establishing some kind of monitoring and reference values to reduce the dose delivered to the most exposed individuals.

But the cancer risk from low level radiation is conventionally estimated from the well-known effects of high radiation doses by use of the linear no-threshold theory (LNT), which on the other hand, seems to be not supported by epidemiological studies. In fact some epidemiological and experimental studies support the existence of a threshold or even beneficial effects at low doses and low dose rates of radiation. According to a very recent study (Preston et al., 2003) there is no direct evidence of radiation effects for doses less than about 0.5 Sv.

There are considerable uncertainties in the estimates of the lung cancer risk from radon in environments other than mines, where in addition, estimates of risk per unit of exposure from different studies on miners, vary by an order of magnitude. The extrapolation from mines to other environments implies a concatenation of uncertainties due to the presence of confounding effects. As an example, in the US, Cole (1993) convincingly argues for a less aggressive radon policy. He demonstrates that the government, to tell the public about the true range of views on the issue impedes citizens from making informed judgments.

Anyway, the solution of this controversy should be let to the radiation protection experts and here the official recommendations and the resolutions only should be considered.

• *International Commission on Radiological Protection*

In 1993, the ICRP issued Publication 65 (ICRP, 1993) by collecting and updating the content of previous publications concerning the dose to both workers and population from radon. Such a report summarises the extent of current knowledge about the health effects of inhaled radon and its progeny and makes recommendations for the control of this exposure in both dwelling and workplaces.

The detriment for members of the public is slightly higher than for workers, due to the presence of children and less healthy individuals among the public. In fact it is assumed that an exposure to 1 mJ h m^{-3} (= 1.80*10^5 Bq h m^{-3} or 4.85*10^6 pCi h m^{-3}) is equivalent to an effective dose of 1.43 mSv for workers and 1.10 mSv for members of the public.

But the ICRP points out that in workplaces used by members of the public, if the public occupancy is low, e.g. in offices, libraries and theatres (and therefore also in caves) these workplaces need no special treatment. This statement simplifies notably the situation by avoiding a different evaluation for workers (cave guides) and members of the public (visitors).

The dose limit recommended by the ICRP (1991) for effective dose is 20 mSv per year averaged over a period of 5 years, with the condition that the effective dose should not exceed 50 mSv in any single year. The corresponding figures for radon are reported in Table 8:

Table 8 - Annual dose limits.

Per year, averaged over 5 years	20 mSv	14 mJ h m^{-3}	4 WLM
In a single year	50mSv	35 mJ h m^{-3}	10 WLM

The ICRP defined also an **action level**, i.e. the concentration of radon at which intervention is recommended to reduce the exposure of individuals. By assuming 2000 hours per year at work and an equilibrium factor of 0.4, the ICRP recommends the adoptions of an action level within the range of 500-1500 Bq*m^{-3} as summarised in Table 9.

Table 9 - Range of the action level.

Lower limit	500 Bq m^{-3}	19 pCi m^{-3}	3 mSv
Upper limit	1500 Bq m^{-3}	56 pCi m^{-3}	10 mSv

• *European Union*

The Commission of the European Communities issued a recommendation (EC, 1997) to provide guidance on the implementation of Title VII (directive on radon) of the Basic Safety Standards (BSS) issued in 1996, for the health of workers and the general public against the danger arising from ionizing radiations. On the whole, these recommendations follow the guidelines set up by the ICRP in Publication 65 (ICRP, 1993).

The EU recommends that "actions levels" should be set in the range 500-1000 Bq/m^3 time averaged radon gas concentration. This is based on occupational exposure of 2000 hours per year and an equilibrium factor of about 0.4. National Authorities may also select an action level below the specific range if they judge this desirable and will not lead to an impracticable radon programme.

Because of diurnal and seasonal variations of indoor radon levels, radiation protection decisions should in general be based on the annually averaged measurements of radon gas or decay products using integrating techniques. It is also recommended that the competent authorities of the Member States should ensure that the quality and reliability of measurements are adequate.

In Table 10 the action levels adopted by different countries are reported. Such levels are designated "advisory reference levels" when they are more or less recommended. When they are stated by laws and official directives and have a binding legal nature, with corresponding penalties, they have been given the designation "enforced reference levels" (Åkerblom, 1999).

Some countries make a difference between existing and new workplaces. Caves are intrinsically "existing" workplaces, but they could be also considered as "new" if a new show cave is being developed. For this reason, when available, both reference values are reported.

In some countries, the local authorities apply different reference values for existing or new workplaces.

In Italy, a reference level of 500 Bq/m^3 for radon is established. If the annual average value of radon is below 80% of the reference value (i.e. 400 Bq/m^3) the measurement must be repeated every three years. If the annual average value of radon is higher, the measurements must be repeated each year.

A conventional conversion factor of 3*10^{-6} mSv of effective dose for each unit of exposure of Bq h m^{-3} is used to evaluate the dose of people. An annual dose delivered to individuals in a cave of 3 mSv from radon exposure is admitted.

In UK, the National Caving Association[1] issued a set of guidelines in consultation with the Health and Safety Executive and the National Radiological Protection Board (NCARWP, 1996). The dose limits for classes of persons are the same recommended by the ICRP as reported above. In addition, the booklet includes useful advises to different kinds of people (private void or land owners, business void or land owners, etc.) for minimising exposure to radon and comply with the UK Health & Safety at Work Act of 1974 and the Ionising Radiation Regulations Act of 1985.

• *USA*

In 1985, the US-EPA evaluated the existing data on the lung cancer risk from radon exposure, and recommended that residents consider taking some kind of remedial action if the radon level in their houses exceeded 4 pCi of radon per litre of air. The EPA projects that if a person is exposed to 4 pCi/L of radon and radon progeny for a lifetime there is an additional 1-5 % chance that the person will die of lung cancer. The EPA does not consider this a safe level of radon concentration, but it is lower than that proposed by some other organisations. The National Council on Radiation Protection & Measurements (NCRP) study says that 8 pCi/L of radon in air is an acceptable level for homes, and others believe the action level should be as high as 20 pCi/L.

The last EPA protocol document contains some clarifications on quality assurance and provides consistent procedures to assure accurate and reproducible measurements, and to enable valid intercomparison of measurement results from different studies (U.S. EPA, 2002). Here prescriptions applicable to caves only are reported.

Short-term tests lasting just two or three days should not be conducted if severe storms with high winds (e.g., > 30 mph) or rapidly changing barometric pressure are predicted during the measurement period. Weather forecasting available on local news stations can provide sufficient information to determine if these conditions are likely.

The detector should be at least 50 centimetres (20 inches) from the floor and at least 10 centimetres (4 inches) from other objects. For those detectors that may be suspended, an optimal height for placement is

[1] *In UK the National Caving Association (NCA) is a federation of caving organisations not to be confounded with the US National Caves Association (NCA) grouping most of the US show caves.*

Table 10 - EU National reference levels for radon gas (Åkerblom, 1999; updated).

Country	Advisory reference levels		Enforced reference levels	
Austria (existing)	400 Bq/m^3	10800 pCi/m^3		
Austria (new)	200 Bq/m^3	5400 pCi/m^3		
Czech Rep.(existing)	200 Bq/m^3	5400 pCi/m^3	1000 Bq/m^3	27000pCi/m^3
Czech Rep. (new)	100 Bq/m^3	2700 pCi/m^3	200 Bq/m^3	5400 pCi/m^3
Denmark (exist. & new)			400 Bq/m^3	10800 pCi/m^3
Estonia (exist. & new)	1500 Bq/m^3	40500 pCi/m^3		
Finland (exist. & new)			400 Bq/m^3	10800 pCi/m^3
Greece (existing)	400 Bq/m^3	10800 pCi/m^3		
Greece (new)	200 Bq/m^3	5400 pCi/m^3		
Hungary (exist. & new)			1000 Bq/m^3	27000pCi/m^3
Ireland (exist. & new)	200 Bq/m^3	5400 pCi/m^3		
Italy (exist. & new)			500 Bq/m^3	13500 pCi/m^3
Latvia (existing)	1000 Bq/m^3	27000pCi/m^3		
Latvia (new)			300 Bq/m^3	8100 pCi/m^3
Lithuania (existing)			400 Bq/m^3	10800 pCi/m^3
Lithuania (new)			200 Bq/m^3	5400 pCi/m^3
Slovak Rep. (existing) (*)			500 Bq/m^3	13500 pCi/m^3
Slovak Rep. (existing) (**)			1000 Bq/m^3	27000pCi/m^3
Slovak Rep. (new) (*)			250 Bq/m^3	6750 pCi/m^3
Slovak Rep. (new) (**)			1000 Bq/m^3	27000pCi/m^3
Slovenia (exist. & new)	1000 Bq/m^3	27000pCi/m^3		
Sweden (existing)			400 Bq/m^3	10800 pCi/m^3
Sweden (new)			200 Bq/m^3	5400 pCi/m^3
UK (exist. & new)			400 Bq/m^3	10800 pCi/m^3

(*) Reference level when the exposure time is less than 1000 hours/year.

(**) Decision level above which the workplace is regarded as a workplace with ionizing radiation source.

in the general breathing zone, such as 2 to 2.5 meters (about 6 to 8 feet) from the floor.

The results of radon decay product measurements should be reported in Working Levels (WL). If the WL value is converted to a radon concentration, it should be stated that this approximate conversion is based on a 50 percent equilibrium ratio. In this case 4 pCi/L (150 Bq/m^3) corresponds to 0.02 WL.

Providers of measurements with active devices are required to recalibrate their instruments at least once every 12 months. Concerning the error affecting each measurement, it is recommended that the total error of any individual device (including both errors in precision and accuracy) be maintained within ± 25 percent of the "true" radon or decay product concentration for concentrations at or above 4 pCi/L (0.02 WL when the equilibrium ratio is 0.5).

In US the Occupational Safety and Health Administration (OSHA) of the Department of Labor has the task of assuring the safety and health of America's workers by setting and enforcing standards; providing training, outreach, and education; establishing partnerships; and encouraging continual improvement in workplace safety and health. Radon exposure is also of concern to OSHA and if there is a guideline that an industry standard is in place, OSHA accepts it, unless they prove that the industry standard is unsafe or not being used. For this reason the National Cave Association (NCA) which groups most of the US show caves, developed precautionary cave radiation standards which OSHA has accepted as an industry standard.

The main issues are here summarised:

Without radon monitoring: underground work shall not exceed 700 hours/year for any employee

With radon monitoring: maximum annual dose limit 4 WLM (20 mSv)

From 0 to 0.1 WL (0-20 pCi/L by assuming F=0.5): annual measurement during the greatest underground working time

From 0.1 to 0.2 WL (20-40 pCi/L by assuming F=0.5): semi-annual sampling

From 0.2 to 0.3 WL (40-60 pCi/L by assuming F=0.5): quarterly sampling

More than 0.3 WL (>60 pCi/L by assuming F=0.5): weekly sampling and record keeping on employee

Smoking in caves, either by employees and visitors, is prohibited.

The cave alpha radiation issue, with reference to the US situation, is specifically discussed by Aley (2000).

• *Other Countries*

In Table 11 the action levels adopted by other countries are reported. As before, such levels are designated "advisory reference levels" when they are more or less recommended. When they are stated by laws and official directives and have a binding legal nature, with corresponding penalties, they have been given the designation "enforced reference levels" (Åkerblom, 1999).

Also in this case, some countries make a difference between existing and new workplaces. Caves are intrinsically "existing" workplaces, but they could be also considered as "new" if a new show cave is being developed. For this reason, when available, both reference values are reported.

MATERIAL AND METHODS

In the previous paragraphs some basic information on radon and the different procedures adopted for the measurements are reported. But radon measurements were considered in general for indoor conditions, both at home and in working places. At the same time, also the remediation to be implemented, in case of values higher than the reference values, consisted both in sealing the possible routes and in ventilation. The special cave environment requires a special approach, which is very different from the usual one. It must be emphasised that in some countries, e.g. UK and Italy, a certified radiation protection expert must issue the report with the results of the measurements and the constraint on the time spent within the cave by the personnel, according to some local regulation.

Material

The very high humidity of the cave environment, which often results in the deposition of a water layer on any surface, is the cause of the malfunctioning of some devices as, e.g., the capacitive sensors for relative humidity.

With reference to active instruments, it is necessary to avoid any water condensation on the electronic circuits, the ionisation chamber, the scintillation cell or the solid-state detectors, particularly when the water film may short-circuit the output. Sometimes also the small amount of heat released by the circuitry is enough to avoid any water condensation. If not, a small lamp inside the cabinet would supply such an amount of heat.

Among the passive detectors, the activated charcoal is in general not suitable for cave measurement because the carbon may be saturated by the water

Table 11 - Other countries national reference levels (Åkerblom, 1999; updated).

Country	Advisory reference levels		Enforced reference levels	
Canada (exist. & new)	800 Bq/m^3	21600 pCi/m^3		
Norway (existing) (*)	400 Bq/m^3	10800 pCi/m^3		
Norway (new)	200 Bq/m^3	5400 pCi/m^3		
Russia (exist. & new)			310 Bq/m^3	8370 pCi/m^3
Switzerland (exist. & new)	400 Bq/m^3	10800 pCi/m^3	3000 Bq/m^3	81000 pCi/m^3

(*) Norway has two advisory reference levels for existing workplaces: 200 Bq/m^3 for simple and inexpensive remedial measures; 400 Bq/m^3 for more expensive measures.

vapour, resulting in a reduction of the radon absorption. Also electret ionisation chambers may be affected by humidity. If, for some reason, such kind of detectors must be used it is convenient to put them inside a sealed polyethylene bag which is permeable to radon but not to water vapour.

The etched track detectors are the most convenient instruments for use in the cave environment, because of their selectivity (they are sensitive to alpha radiation only and absolutely not affected by beta or gamma radiation) and their intrinsic robustness.

Methods

When radon monitoring in a cave is required for the first time, it is convenient to carry out a preliminary short survey with an active instrument in order to obtain an indicative value of the radon concentration. When such a value is known the most suitable type of detector and its exposure time can be properly identified.

Since radon concentration varies in a rather wide range with time, as it was reported before, it is advisable to carry out measurements as long as possible (weeks or months, preferably) to avoid the influence of unusual peaks which may occur without any apparent cause. In addition, when a continuous monitoring is not possible, the measurements should be repeated in different seasons in order to obtain a value of the radon concentration averaged over at least one year, as required by regulatory authorities. In fact there is a seasonal and nyctemeral variation of the radon response to environmental stress resulting in seasonal and diurnal periodic variations.

The detectors should be placed approximately in the middle of a cave passage and possibly suspended in the general breathing zone, such as 1.5 to 2.5 metres from the floor. In any case the detector should be at least 0.5 metres from any surface.

Limits implementation.

The general methods used for remediation cannot be adopted in caves as it was reported above. Since it is neither possible nor advisable to change the cave atmosphere, the only way of complying with the radiation protection regulation for the people exposed to radon, is the limitation of the exposition time of the individuals.

Once a series of measurements is carried out according the rules established by the regulatory authorities, yearly average value of radon concentration can be obtained. Since ICRP, EU and OSHA accept an annual dose limit of 20 mSv (corresponding to 4 WLM with an equilibrium factor of 0.4), the diagram of Fig. 6 can be used to calculate the hours that an individual can spend in the cave at a given average radon concentration, with an annual dose limit of 20 mSv. Also annual dose limits of 10 and 3 mSv are reported to take into account different regulations.

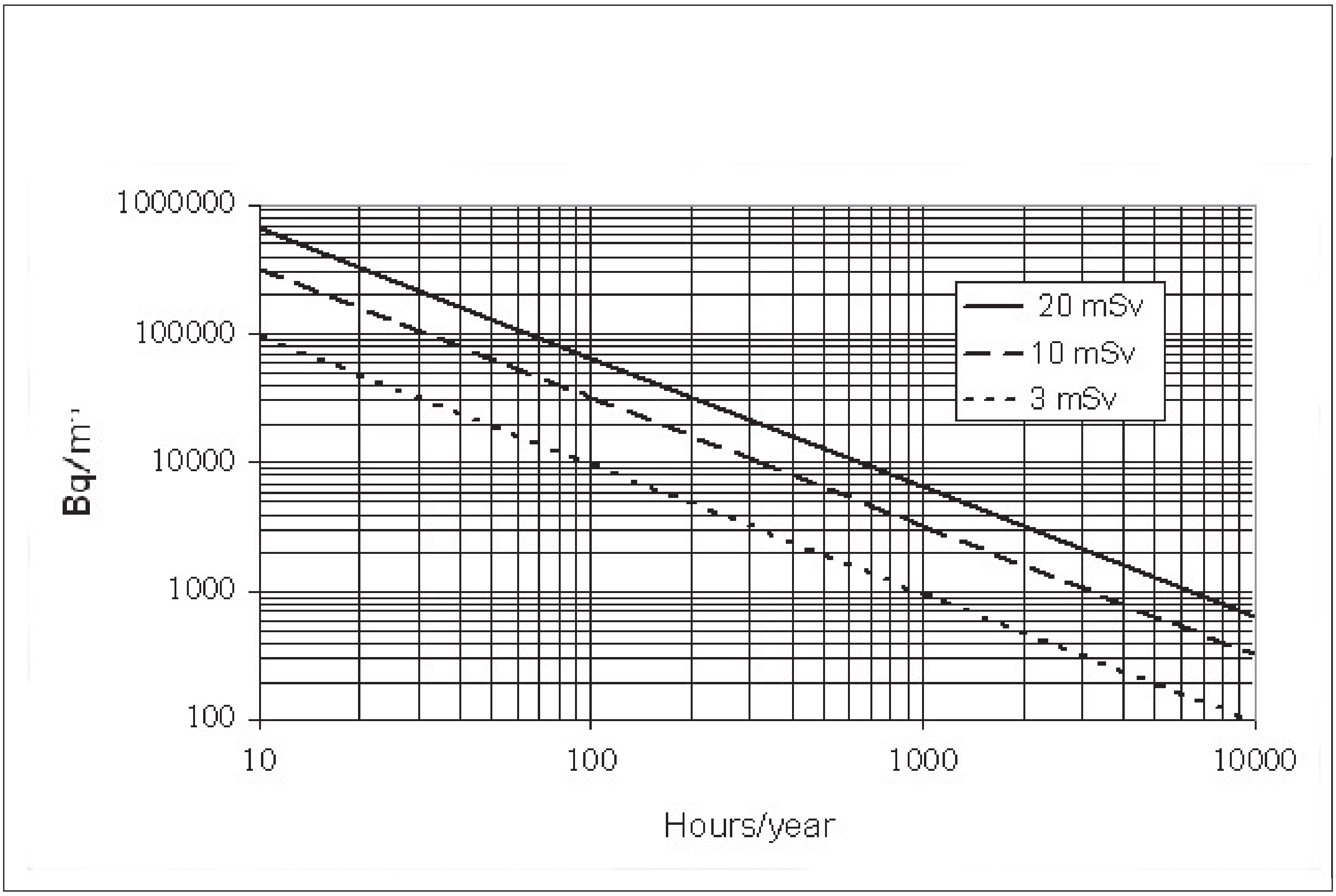

Fig. 6 - Hours per year which can be spent with annual dose limits of 20, 10 and 3 mSv respectively and an equilibrium factor of 0.4.

The general relationship between the average radon concentration and the time, which can be spent in a cave during one year, is given by the equation:

$$T = \frac{10^6*D}{7.784*F*C}$$

where:
T = hours/year
D = annual dose limit, mSv
F = equilibrium factor
C = average radon concentration, Bq m^{-3}

Therefore, by means of this equation it is possible to calculate the time which can be spent in a cave for any given average radon concentration, equilibrium factor and annual dose limit, according the local regulations.

Other remarks

It must be recalled here that, some radon exposure may arise also outside the cave itself, but in its vicinity. In fact, some show caves have constructed buildings over the cave entrance, and in many cases these buildings are routinely occupied by employees. This may alter the natural microclimate of the cave and deliver a dose from radon exposure also indoor. Clearly any modification of the natural microclimate of caves must be avoided. In addition, if the cave air enters the building then employees in the building receive an unjustified exposure from radon.

In a show cave monitored for radon, it was found that employees in the surface building were getting higher doses than the cave guides. In these cases radon indoor must be monitored also and, if necessary, mitigation must be implemented. But in general, buildings should never be constructed over caves to avoid the problems reported here.

There are several show caves where visitors enter on elevators, connected to a visiting centre. The elevators often serve to pump cave air into the buildings. Indoor radon concentration can be lowered if the elevators are in a separate room where air is exhausted to the outside rather than letting it enter the remainder of the visitor centre.

If a show cave has a radon concentration close to the limit established by the local regulation, optional activities, like underground lunchrooms, should be avoided. In principle, also major maintenance and construction work in a cave should be carried out during periods of the year when radon concentration is the lowest (Aley, 2004).

CONCLUSION

Radon is a rather peculiar component of the cave atmosphere. It can be an important tool to study the cave microclimate as well as other interesting processes. Variation in radon concentration is subject to such a large number of reasons, which make it sometimes difficult to obtain a reliable information.

In the past, radon was supposed to supply useful predictions of earthquakes (Shapiro et al., 1980; Smith et al., 1980). The connection between sudden variations of the radon concentration and earthquakes was confirmed but, as such variations may be due to many other reasons, it is possible to verify this warning by radon only after the earthquake occurred.

Anyway, it is outside the scope of this paper to discuss the different possible kinds of research based on radon because they are already well known by radon specialists. The aspect of radiation protection of individuals working in a cave (as well as in any other underground environment) became very important recently.

As it was reported earlier, much estimation of the deaths attributable to the dose delivered by radon are possibly overestimated. But this point is outside the scope of this work, because the scientific debate on the real role played by radon from the health point of view has not reached any firm conclusion.

Care should be taken for the compliance with the local regulation for cave activity issued by the authorities for any person working in an underground location. It must be emphasised that such a compliance can never be obtained by any modification of the cave atmosphere, e.g. by ventilation. Such a relevant disruption of equilibrium of the cave environment cannot be justified on account of the serious consequences on the cave environment. Therefore, the compliance with limit to the dose delivered to cave workers can be achieved uniquely by limiting accordingly the time spent by them in the caves.

When cavers are considered two points should be taken into account: they are generally healthy and the ordinary risks they face in their work are much larger than the risk deriving from the exposure to radon at the concentrations normally found in caves. Therefore, there are no reasons to limit the time spent in caves by cavers for radiation protection constraints unless the radon concentration in the cave is exceptionally high. A similar consideration can be made for tourists and/or cave amateurs because they spend a rather short time in caves also in the case of persons very fond of them.

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