3.6.3. Radon Measurements

Caves are commonly considered as a static environment where, in complete darkness, parameters as temperature and humidity are stable. But other parameters may experience very high variations due to many exchanges between the cave air, the fracture system, the outside, the sediments and the water in the cave. Air radon concentration is one of these parameters which undergoes high dynamics in response to changes of other factors of the environment.

In a long-term study of radon concentrations in mines or caves, it is important to analyze the interactions of meteorological, climatic and pedologic factors which affect radon concentrations on minutely, hourly, daily, and seasonal time scales. A simultaneous measurement of other gases is often of great interest. The installation of an external weatherstation is mandatory as radon levels are always correlated to some extent with outside air temperature, atmospheric pressure, wind speed, humidity and rainfall. Depending on the time-scale of the study, daily or seasonal, not all the parameters mentioned are needed.

3.6.3.1.Seasonal Radon Pattern

Fig. 3.6.3 shows the result of monitoring radon over three years, based on nuclear etched track integrating measurements exposed in the three interior stations. The seasonal pattern is mainly the result of air movements due to differences of external and internal air densities caused by varying external temperatures, the internal temperature can be considered as constant. This is a classical temperature-induced air movement (chimney effect) in underground locations which have openings to the exterior situated at two different levels at least. The observed radon pattern, with maximum values in those periods, autumn and spring, when inside-outside temperature differences are minimal, can be interpreted if one admits the existence of one or more systems of galleries under the explored cave, some of which communicate to the outside via small openings and fissures in the cliff (see chapter 1.1.).

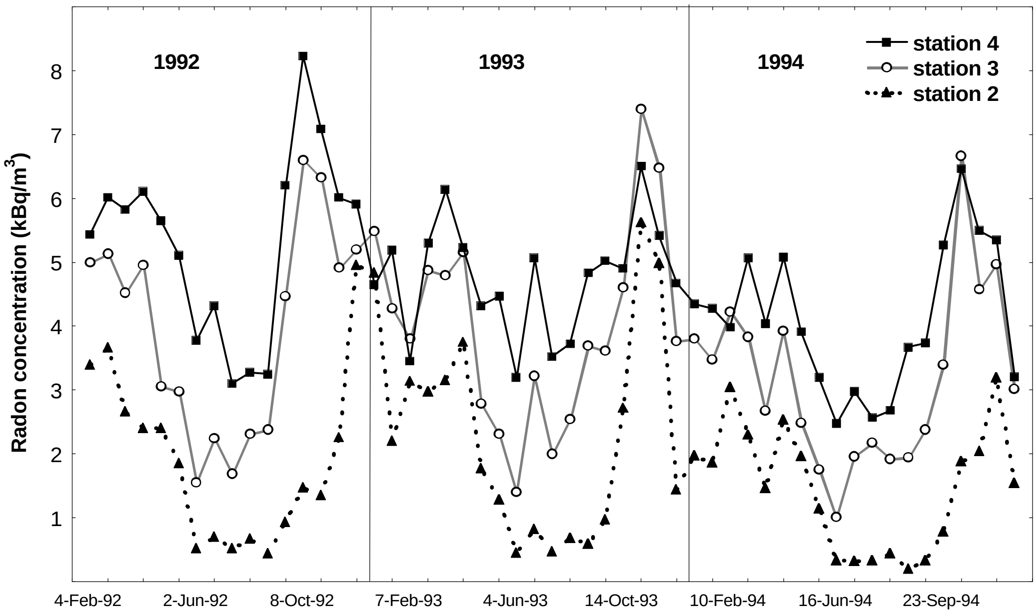

Fig. 3.6.3. Time evolution of mean radon concentrations over three years in three different locations in the main gallery, at 12 m (st. 2), 31 m (st. 3) and 50 meters (st. 4) from the entrance.

In the *cold period*, the lighter radon-enriched air of the system rises, and pushes cave air out through the exit. During this movement, the air gets enriched in radon from the fracture system and from the sediments. The radon levels in the cave are highest when these air movements are very low, this happens at temperatures slightly below the cave temperature of 9.5°C as seen on fig. 3.6.4. Higher temperature differences move a greater air volume, thus the speed of air flowing through the fracture system is increased, and as a consequence the radon concentrations of the air entering the cave galleries from below decrease.

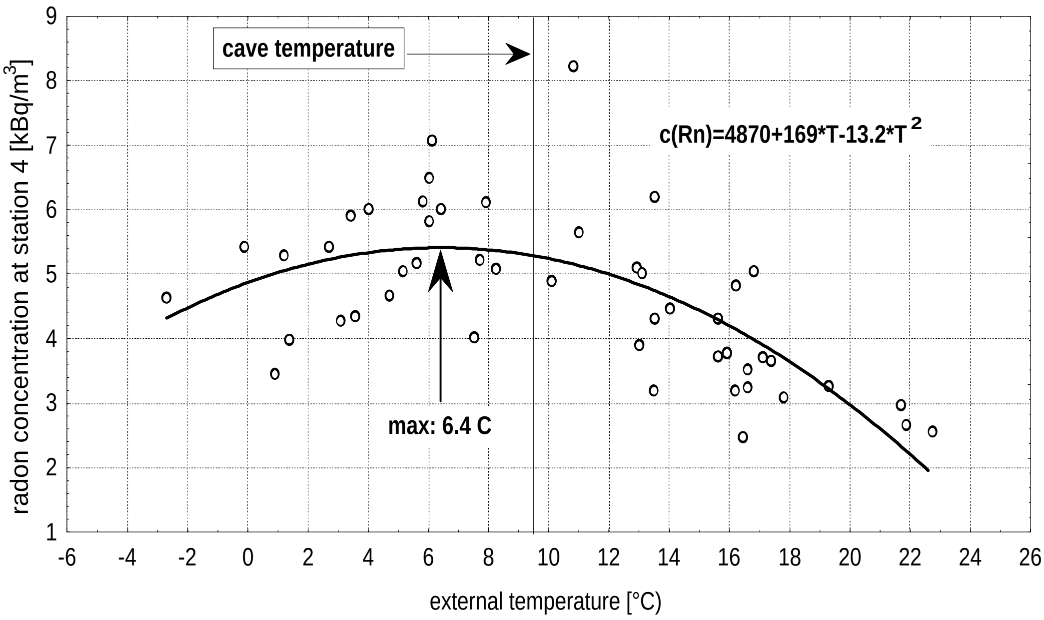

Fig. 3.6.4. Radon concentration at station 4 in the Moestroff cave, 50 meters from the entrance, against temperature can be fitted by a parabola.

In *summer*, the process reverses, the direct inflow of outside air into the cave leads to the lowest radon concentrations. This effect is most effective for locations near the entrance.

There is a slight asymmetry in the way the radon changes between summer and winter. In springtime, radon levels in the cave vary gradually whereas in the fall they experience a rapid increase.

The radon transport processes depend essentially on the configuration and the connection of the underground cavities, passages and other communications to the exterior, such as fissures and fractures. Due to the particular location of the Moestroff multi-storey cave, with an upper main gallery and with openings on a cliff, the seasonal radon pattern is quite different from those reported elsewhere for caves [Hingmann et al., 1995; Hunyadi et al., 1990]. For horizontal caves and for caves with most passages above the entrance elevation, a typical pattern of temporal radon changes are summer maxima and winter minima [Kies et al., 1995]; in caves where most passages are below the entrance, but with no communication to the exterior, the wintertime air stagnation in the cave results in high radon concentrations during the cold season. [Kies et al., 1993; Haql et al., 1996].

We explain the air movements and the seasonal radon behaviour, essentially governed by the chimney effect, by the existence of not accessible galleries below the actual cave with multiple small openings in the cliff. In the cold season, radon-enriched air entering the cave from below leads to higher radon concentrations than in the summer when fresh air entering the cave through the main entrance is loaded gradually with radon during its movement through the cave. In summer with the main inflow of air through the entrance, radon concentrations (in kBq/m^3) experience a linear increase.

$$c(x) = 0.018 + 0.083 * x \qquad \textit{[eq. 3.6.1]}$$

with the distance x to the entrance; in winter when the cave exhales, a higher exponential increase

$$c(x) = 5.4 * (1 - e^{-0.065 * x}) \qquad \textit{[eq. 3.6.2]}$$

is observed (fig. 3.6.5).

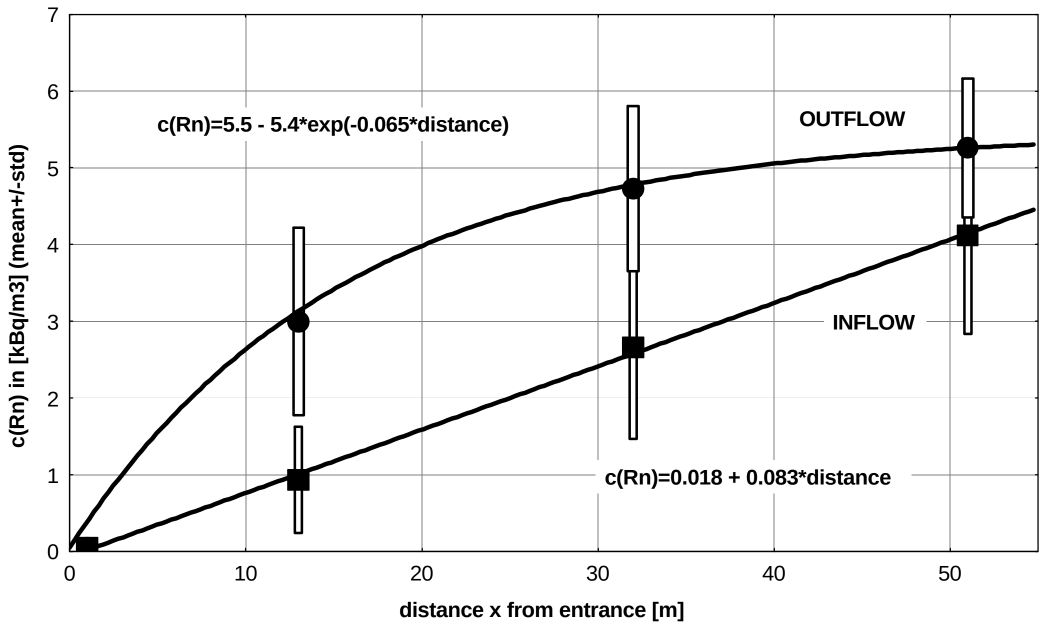

Fig. 3.6.5. Radon versus distance from entrance

Equation 3.6.2 is a steady state solution of the one dimensional transport equation due to radon production, decay and molecular diffusion and to fluid flow in a cylindrical void embedded in a rock matrix [Clements et al.,1974; Bates, 1980; Nazaroff, 1992]:

$$\frac{dC}{dt} = D\Delta C - \nabla(\bar{v}C) - \lambda C + \Phi \qquad \textit{[eq. 3.6.3]}$$

where

C radon concentration in pore space [m^{-3}]

D diffusion coefficient of radon [m^2*s^{-1}]

v velocity of air carrying radon [$m*s^{-1}$]

λ decay constant of radon [s^{-1}]

Φ radon source term [m^3*s^{-1}].

A particular steady state solution of this equation, assuming a constant velocity v and the boundary conditions:

$$C(0,t) = C_0 \approx 0, C(\infty,t) = C_\infty = \frac{\Phi}{\lambda} \quad \textit{[eq.3.6.4]}$$

is $$C(z) = C_\infty(1 - e^{-\frac{z}{l}}) \quad \textit{[eq. 3.6.5]}$$

where l is the characteristic transport length. For the Moestroff cave this characteristic length is is approximately 15 m, very close to the relaxation distance found for the temperature profile (see chapter 3.1).

The variation of mean radon concentration with external temperature is quite different at the three stations. If no distinction is made between inflow and outflow periods, the best overall fits are linear for stations2 and 3, and parabolic for station 4 (fig. 3.6.6).

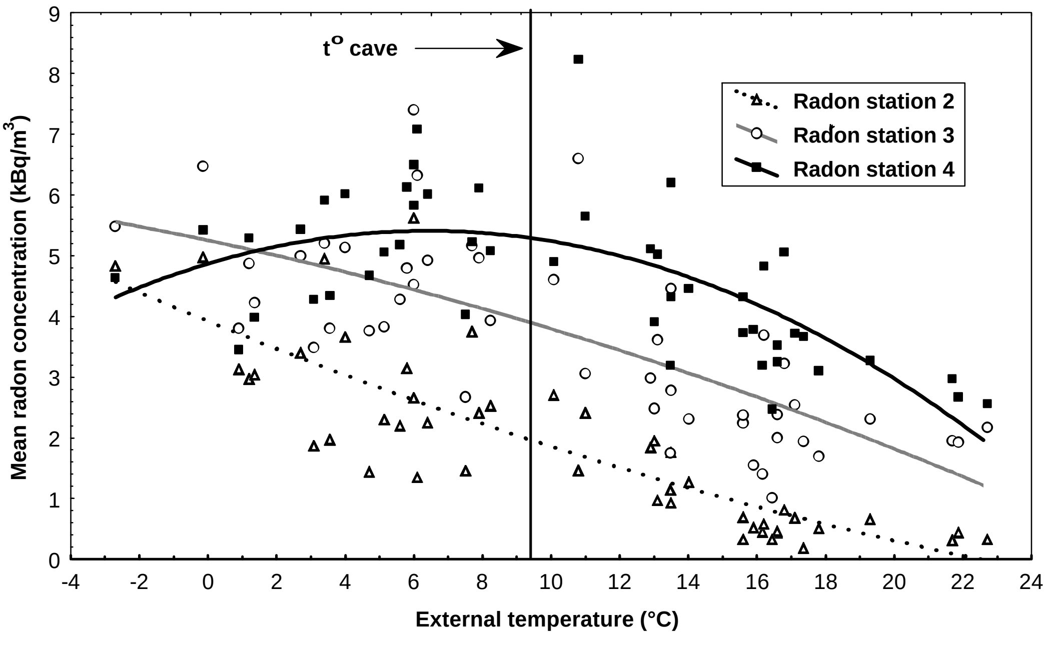

Fig.3.6.6. Variation of c(Rn) with outside temperature

Near the entrance at **station 2**, radon concentrations continuously decline with increasing outside temperature; under very cold weather conditions the exhaling radon-enriched air has a concentration of 5 kBq/m^3, which is the steady state radon concentration of the interior of the galleries. Increasing outside temperatures lower the exhalation which gradually changes to inhalation of fresh air. At the deepest located **station 4**, the changes in mean outside temperature have the smallest effects on radon concentrations, but even this location experiences the diluting effect of the important thermally induced air movements especially in summer. The interposed **station 3** has an intermediate behaviour in the cold season when stations 2 and 4 experience an opposite evolution, which leads to a near constant mean value of 5 kBq/m^3.