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Creators: Gillmore, G. K., Gharib, H. A., Denman, A. R., Phillips, P. S. and Bridge, D.

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Radon concentrations in abandoned mines, Cumbria, UK: safety implications for industrial archaeologists

G. Gillmore¹, H. Alizadeh Gharib¹, A. Denman², P. Phillips², and D. Bridge³

¹Kingston University, Geography, Geology and the Environment, Kingston-upon-Thames, UK

²University of Northampton, School of Science and Technology, St. Georges Avenue, NN2 6JD, Northampton, UK

³Cumbrian Amenity Trust Mining History Society (CATMHS), 3 Brigham Hill Mansion, Brigham, Cockermouth, Cumbria, CA13 0T1, UK

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Abstract. This paper presents a number of surveys performed in a geographical area of the UK, part of which until recently was considered low radon risk. The Cumbrian region was identified by the Building Research Establishment (BRE) in its 1999 guide as an area without a significant radon problem in the built environment. The geology of the region, which includes the Northern Pennine Orefield is varied, but consists of granites, andesites, tuffs, carbonates, sandstones and shales. Mineralisation has taken place (mostly lead and copper ores) primarily along fault and fracture zones, one example being Copper Valley, northwest of Coniston village. This work quantifies the risk of exposure to radon in a number of abandoned mine environments. High radon levels, up to $28\,589\text{ Bq m}^{-3}$, have been measured in parts of one mine. This study demonstrates that industrial archaeologists (such as the Cumbrian Amenity Trust Mining History Society or CATMHS members) and explorers of abandoned mines can be at risk from radon exposure and it proposes a management scheme to allow industrial archaeologists to continue exploration whilst minimising the risk to health from radon.

1 Radon and safety

There is considerable evidence to show that excessive radon levels in some mines cause lung cancer in miners (BEIR, 1999), and that the increase in lung cancers follows a linear relation with the increasing radon level. The International Commission on Radiological Protection (ICRP) have concluded that excessive radon levels are a health hazard (ICRP,

1993) in homes and workplaces. In a recent study by Darby et al. (2005), it was shown that a modest risk from radon extends down to 100 Bq m^{-3} in domestic housing in line with the linear no-threshold theory.

In 1990, the UK National Radiological Protection Board (now the Health Protection Agency or HPA), proposed an Action Level of 200 Bq m^{-3} for domestic properties (Miles et al., 1992). An additional Target Level has recently been recommended (McColl et al., 2010) by the HPA of 100 Bq m^{-3} for domestic indoor radon in the UK following the World Health Organisation recommendations (WHO, 2009). Employers are also now required under the Ionising Radiation Regulations (IRR, 1999) to remediate if levels are above 400 Bq m^{-3} , or the area must be declared a Controlled Area with limited access. For other ionising risks, in order to limit the risk of cancers, IRR99 specify a 1 mSv annual dose limit for members of the public, 6 mSv for radiation workers and 20 mSv for classified workers, who are required to have annual health checks. Calculating the radiation dose received from radon exposure can be useful when considering the risk to people occasionally exposed to radon and Denman et al. (1999) have shown that, in the built environment, full-time workers exposed at 400 Bq m^{-3} receive radiation doses close to, but below, the 6 mSv limit.

The HPA have demonstrated that several regions in the UK have elevated radon levels, a number being designated as “Affected Areas” (these are defined by greater than 1% of dwellings being above the Action Level; Miles et al., 1992). In Cumbria the Building Research Establishment (BRE, 1999) guide suggests that radon levels are such that generally no radon protection is required in new houses, although the guide does suggest that in the area of the mines a geological assessment should be undertaken prior to building. Additional measurements in houses and a detailed



Correspondence to: G. Gillmore
(g.gillmore@kingston.ac.uk)

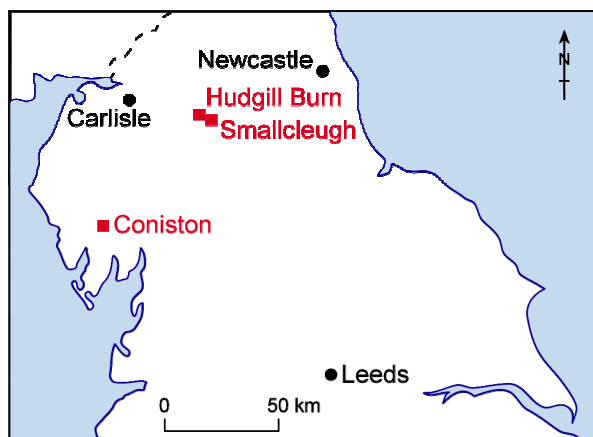


Fig. 1. Location map of Hudgill Burn, Smallcleugh and Coniston mines in Cumbria.

geological analysis by the British Geological Society has recently resulted in the publication of higher resolution maps (Miles et al., 2007) showing areas of high radon potential within the study area and revised BRE guidance for domestic housing (BRE, 2007). The 2007 maps indicate that in the village of Coniston, greater than 30% of the homes are above the Action Level, although the area of Coniston Copper Valley is identified as potentially having between 0–1% and 1–3% of homes above the Action Level. This may be because there are very few homes close to the mines that the immediate area is shown as a relatively low radon area. The Smallcleugh and Hudgill Burn mines on the other hand occur in the Nenthead area in Cumbria and this region is identified as having between 5–10% and 10–30% of existing homes with radon levels above the Action Level in the 2007 map guide (Miles et al., 2007).

2 Geology and mining history

Hudgill Burn (Fig. 1) was a lead mine, which also contained silver deposits. The ore veins are unique in the Pennine Ore-field not only for their structure, but also for the abundance of cerrusite (Dunham, 1990). The richest deposits were found in the thick grey-blue, fine-grained Great Limestone (Dunham, 1990). The mine was worked from 1814–1870, produced 54 642 tons (approximately 55 519 metric tonnes) of lead concentrates and from 1854–1870, 13 oz (368.6 grams) of silver per ton (1.016 tonne) of lead (Dunham, 1990).

Smallcleugh Mine (Fig. 1) started around 1770 as a lead mine, with 4999 tons (5079 tonnes) of lead concentrates being extracted for the period 1848–1882. It contains ankerite, galena and sphalerite (zinc ore). There are also sulphate minerals in the form of epsomite (magnesium), melanterite (iron) and devilline (copper) together with annabergite (nickel; Dunham, 1990).

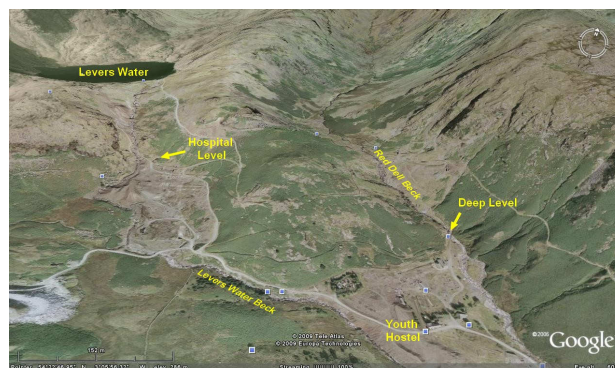


Fig. 2. Oblique aerial view of the Coniston Copper Valley and the mines visited during the 2008/09 survey. Arrows point out entrances to workings explored. Squares indicate mostly mine-related Google points of interest (© Google Earth 2009).



Fig. 3. Cross-cut to Brimfell, Paddy End mine, Coniston. The wall rock is crumbly, grey tuff and the ground is covered in iron-stained mud and sand-sized weathered material. Notebook held by D. Bridge.

Coniston Copper mines (Figs. 1, 2, 3) lie in a region of hard volcanic rhyolite and andesitic lava interbedded with hardened and cleaved tuffs/ashes. Mitchell (1940) and Millward et al. (1999) have shown that the mineral veins that occur in faults and fissures are wide and productive within acid wall rocks, but are poor in andesite, andesitic tuff and volcanoclastic sandstone. South of Levers Water, these mineral veins trend southeast. From the early 17th century Paddy End mine was exploited for copper (see Fig. 4), the primary ore being chalcopyrite. Other metallic minerals include magnetite, iron pyrites, arsenopyrite and nickel and cobalt (Holland, 1981). In the late 19th century, Coniston copper mines produced more than 50 000 tons of dressed ore with 5–13 wt% copper, along with 12 tons (12.19 tonnes) of lead and 3 tons (3.05 tonnes) of cobalt and nickel ore (Firman,

1978). The mines in the valley visited in this study also included the Bonser (alternative spelling “Bonsor”) Mine.

Since the 1950s, the copper mines of Coniston have been of historical interest and have continued to attract explorers, historians and tourists (Bridge, 2000). The abandoned Coniston mines are now undergoing a new phase of mineralization prompted by the empty space left behind after the cessation of mining activity. Colourful minerals such as erythrite, goethite, malachite, and limonite are gradually being deposited in and on walls, roofs and floors of adits and shafts.

Copper slag dumped from mining operations in the 19th century along Coniston water (e.g. at Moor Gill Foot, SD 297939) have been blamed for the pollution and the observed lower diversity in biota of the lake (Millward et al., 2000).

3 Methods

Radon levels were measured in August–September in 2000 and December 2000–January 2001 using commercial alpha track-etch CR39 detectors and at one mine in June 2008 and February–March 2009 using an in-house Radosys track-etch system, following the method laid out by Green et al. (1992) (Appendix A: Measurement methodology). Appropriate Quality Audit and Quality Control procedures were applied to both the laboratory and field procedures. The Kingston University laboratory is a Health Protection Agency, accredited radon testing facility and takes part in yearly European wide laboratory intercomparison studies. The Radosys system is also calibrated by the manufacturer for each new batch of track-etch detectors. The Radosys system was operated then, as described previously, by Gillmore and Jabari-vasal (2010). Radon gas forms tracks in the CR39 plastic, with a linear response up to $5000 \text{ kBq h m}^{-3}$. CR39 has a lower detection limit of around 50 kBq h m^{-3} . The exposure times were chosen to fit in this range, but accessibility issues resulted in some exposure times being close to the upper limit. For the later set of measurements, a manual counting check was also conducted to confirm the accuracy of the automatic system.

The detectors were left underground for between 6 and 35 days for the 2000/01 for up to 28 days for the 2008/09 season. Several volunteer industrial archaeologists wore CR-39 detectors on the outside of their clothing to assess personal exposure (referred to as personal detectors in this paper) for the duration of their mine visits.

During the installation at each mine locality, each detector was positioned at about 1 m above the ground. Every location in Coniston Copper Valley during the second visit was assigned a number and detectors were photographed in situ. Brief descriptions of the location and detector numbers were written in a field notebook and locations marked on the mine plan. In autumn and winter visits, air conditions (temperature and humidity) and the direction of air flow within the mine were recorded when possible.



Fig. 4. Secondary copper mineralization near Paddy End Shaft. Field notebook held by D. Bridge.

4 Results

The radon levels from Hudgill Burn mine varied from 924 Bq m^{-3} to $28\,589 \text{ Bq m}^{-3}$ (Table 1). The radon concentration at the active archaeological dig during winter 2000/01 in this mine, which was at the 1st Sun vein, was $17\,183 \text{ Bq m}^{-3}$. The third measurement period was somewhat disturbed by the national foot and mouth emergency in 2001 which meant that detectors had to be left in place for almost a year due to access difficulties over farmland. The results demonstrate a typical seasonal variation in caves with lower levels in winter than summer, the reverse of the situation in the built environment.

Radon levels in Smallcleugh mine, measured in the summer, were lower (Table 2), and varied from 805 Bq m^{-3} to 1695 Bq m^{-3} . These levels were lower than the $27\,000 \text{ Bq m}^{-3}$ suggested from a previous brief survey of north Pennine caves (D. Bridge, CATMHS, personal communication, 1998). There are several possible reasons for this – varying from measurements being taken at a different time or even position within the mine, to improved ventilation and flooding.

At Coniston Paddy End mine (Table 3, Fig. 5) radon levels varied from 80 Bq m^{-3} to 2152 Bq m^{-3} in 2000–01. The latter mine was revisited in 2008/09 as part of an undergraduate dissertation project (Alizadeh Gharib, 2009; see Table 4). Many of the detectors on this second visit were placed in similar positions to the first set of detectors. Some were placed in a number of additional positions within the Copper Valley mines area, the highest reading being from one of the deepest parts into the mine. Higher radon concentrations were noted in the region of 4727 Bq m^{-3} in June 2008, whilst in the spring the high was 984 Bq m^{-3} and shows the same seasonal variation as the Hudgill Burn mine.

Table 1. Radon concentrations measured in Hudgill Burn Mine.

Position	Radon (Bq m^{-3})		
	6 to 12 Aug 2000	16 Dec 00 to 13 Jan 01	17 Feb 01 to 13 Jan 02
Blocked Level at Forehead. Just below Great Limestone	28 589		
Blocked Level at Forehead. Just below Great Limestone	18 478		
North Vein in blind heading in the tuft below Great Limestone	17 197	13 391	2472
450 m from entrance in the tuft below Great Limestone	15 975	8238	2469
10 m from entrance in shale	9460	924	2245
Dig on 1st Sun Vein		17 183	2472
Rise			2413

Table 2. Radon concentrations measured in Smallcleugh mine.

Position	Start	Finish	Radon (Bq m^{-3})
45 m from entrance in a flat	12-Aug-00	16-Sep-00	805
Elliot's string in blind heading – Limestone	12-Aug-00	16-Sep-00	1337
Gully back cross cut blocked level	12-Aug-00	16-Sep-00	1028
Gully back cross cut blocked level	12-Aug-00	16-Sep-00	1695
10 m from entrance	12-Aug-00	16-Sep-00	203

Table 3. Radon concentrations measured in Coniston Paddy End mine.

Location	Start	Finish	Radon (Bq m^{-3})
Top Level – Blind Spur	13-Nov-00	24-Jan-01	289
Top Level – Junction	13-Nov-00	24-Jan-01	2152
Arete Chamber	13-Nov-00	24-Jan-01	97
Top Level – Green Channel	13-Nov-00	24-Jan-01	80
Middle Level – Blue Rock	13-Nov-00	24-Jan-01	592
Grey Crag Level – Blind – 270 m from portal	07-Jan-01	18-Jul-01	251
Furthest Point Puddingstone Level	07-Jan-01	18-Jul-01	826

5 Risk to industrial archaeologists

Denman and Parkinson (1996) estimate the dose received from radon to occupants in the overground workplace, schools and domestic properties using the following formula, which was applied by Gillmore et al. (2001) to mines.

Dose (mSv)

$$= \frac{(\text{Radon Concentration, Bq m}^{-3}) \times (\text{duration, hours})}{126\,000}$$

The above equation assumes an Equilibrium Factor (F) of 0.5.

The risk is, therefore, dependent on the time spent in a mine and the radon level at that point. All three mines had

some parts with radon levels over 400 Bq m^{-3} , so that full-time workers would receive a dose in excess of the legal limit if working in that part all year. For example, a worker spending 37.5 h a week working at the North Vein of Hudgill Burn Mine all year, where the annual average radon level was found to be 2472 Bq m^{-3} , would receive a dose of 34.2 mSv. This assumes that this average is correct noting comments above regarding access difficulties for detector removal. On the other hand, an archaeological explorer making 4 visits to Elliot's string in the Smallcleugh mine in summer would receive 0.12 mSv, much lower than the dose limit. Archaeological teams work underground most Sundays when they are opening up a level, working for about 6 h over a period of weeks or months. Some keen explorers go underground regularly throughout the year and might spend several hours

Table 4. Radon concentrations measured in Coniston Copper Valley, 2008/09. Detectors at sites 3 and 13 were not recovered. The Detector at site 3 because of a roof collapse.

Site No.	Location	Radon (Bq m^{-3})		Conditions	
		2 to 29 Jun 2008	22 Feb to 22 Mar 2009	2 to 29 Jun 2008	22 Feb to 22 Mar 2009
1	Junction of Bonser Vein & Deep Level Cross-cut	511	88	No running water	water dripping from ceiling
2	Dead end, North Cross-cut	727	90	Dry	
4	Small cavity near junction of Deep Level Cross-cut and Bonser Vein	517	82	near 2–3 cm running water	
5	25 m inside Deep Level Cross-cut, dry walls	529	84	dry walls, 2 cm running water	
6	Paddy End Mine, 150 m in Cross-cut to Brim-fell	1322	758		
7	Spur, near collapsed stope	789	140	Dry	
8	8 m long spur near Gin Chamber in Bel-man Hole Vein	873	261		
9	Triddle Vein, dead end, cleaved mineral vein	3495	2173	1–2 cm water	1–2 cm water
10	Junction of Cross-cut & North Cross-cut, pink erythrite	3998	2373	4–5 cm water	dry
11	Junction of 2 faults, unstable wall rock	4727		vapour in air	
12	50 m inside Hospital Level	663	91	dry ground	
14	Taylor's Level, 30 m inside adit		33		dry
15	Paddy End Mine, Bel-man Hole Vein, spur to left of adit, 2 cm water		984		2 cm water
16	Courtney's Cross-cut		96		10 cm water
17	Kernal Vein, at adit entranceway, adit heavily faulted		145		5 cm water
18	90 m inside Gaunt's Level		144		20–25 cm water near entranceway, wet wall rock

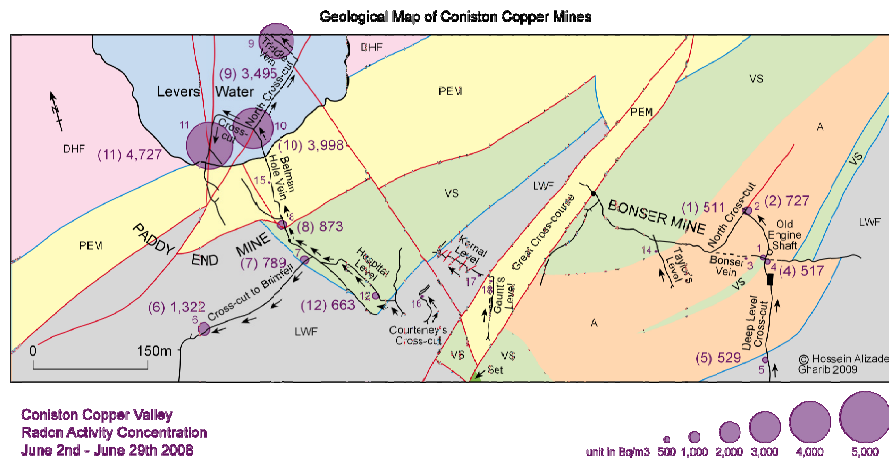


Fig. 5. Radon Activity Concentration map of the mines in Coniston Copper Valley, for 2 to 29 June 2008. Red-purple circles represent radon concentration in Bq m^{-3} . Black arrows are the direction of movement within the mine workings. DHF is the Duddon Hall Formation andesitic tuff; PEM is Paddy End Member rhyolitic tuff; LWF is Low Water Formation lapilli tuff and lapilli; VS is bedded tuff and volcanoclastic sandstone; A is andesite; and Set is Seathwaite Fell Formation volcanoclastic sandstone. Red lines are faults, black lines are mine adits covered in this survey.

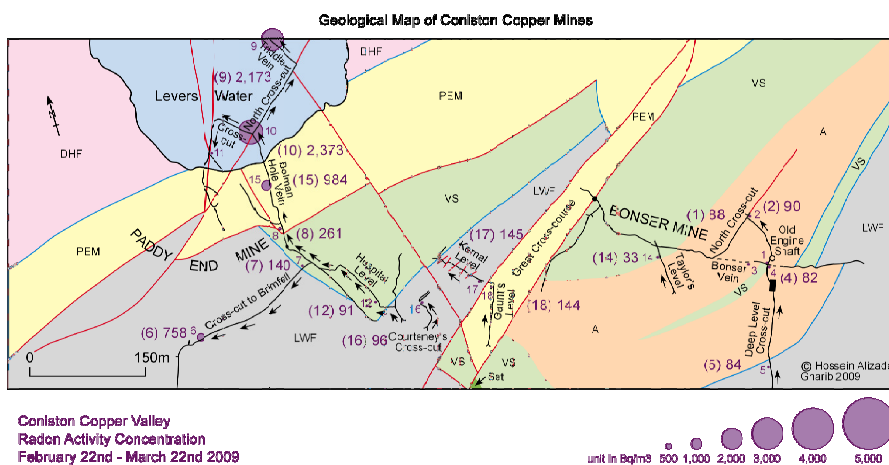


Fig. 6. Radon Activity Concentration map of the mines in Coniston Copper Valley, for 22 February to 22 March 2009. Red-purple circles represent radon concentration in Bq m^{-3} . Black arrows are the direction of movement within the mine workings. DHF is the Duddon Hall Formation andesitic tuff; PEM is Paddy End Member rhyolitic tuff; LWF is Low Water Formation lapilli tuff and lapilli; VS is bedded tuff and volcanoclastic sandstone; A is andesite; and Set is Seathwaite Fell Formation volcanoclastic sandstone. Red lines are faults, black lines are mine adits covered in this survey.

a week at different mine sites. There is no particular preference for winter or summer working, although winter activities are dependent on weather conditions due to more limited mine access.

As can be seen, the dose received by visitors to mines can be limited by restricting the time spent in the mine. In addition, if there is a known radon risk, radon monitors can be worn by the individuals concerned. The simplest detector is the track etch detector, but this is only assessed retrospectively.

It should be noted that F in mines varies widely (Gillmore et al., 2001). F is likely to be the lowest at the entrance, where values down to 0.04 have been recorded, where the radon can diffuse into the atmosphere, and the highest is deep in the mine where there is little or no ventilation. In such circumstances, F can reach 0.95 (Langridge et al., 2010). Whilst some studies assume F of 0.2 (e.g. NPRB report M667), in our experience, 0.4 to 0.5 is not atypical of accessible cave and mine systems.

6 Action: advice to industrial archaeologists

Show caves and mines are subject to the IRR (1999) and, hence, monitored and regulated by the Health and Safety Executive (HSE) or local authority Environmental Health Officers (EHO), to protect people working as guides. Owners of abandoned mines who allow visitors are also subject to the same regulations. As shown by this example, radon maps of radon levels in the built environment may not be an accurate guide to the risk from radon in underground works, and it would be an advisable safety check to place a radon monitor in any newly discovered old mine. Work by the authors (Gillmore et al., 2001) suggests that metallic ore mines appear to have raised risk of high atmospheric radon concentrations.

In 2000, Hudgill Burn mine was being actively opened up by CATMHS. In January 1998, CATMHS gained access to a large part of the old lead workings, as well as a 300 m long natural cavern. The society is still actively opening up the mine system. In the light of this, a study was undertaken on radon levels and the potential health effects and risks to volunteers.

There is considerable seasonal variation in the results for the entrance to Hudgill Burn mine (Table 1), but levels within the mine vary less. In many mines and caves, higher radon levels have been associated with wet weather and it may be that the December 2000 levels are higher than normal because of the higher than average rainfall. However, the seasonal variation found is within the range of seasonal variations noted in the literature (Gillmore et al., 2001).

These levels should be compared with the Action Level for workplaces of 400 Bq m^{-3} defined in the Ionising Radiations Regulations (1999). As the level within Hudgill Burn mine cannot be altered by forced ventilation, there is a legal onus on industrial archaeological organisations to ensure that doses received by volunteers are restricted to the legal limits. This can be done by limiting the time spent in such a mine as Hudgill Burn and monitoring the dose via personal radon detectors.

As shown above, once radon levels are known, it is possible to estimate the maximum time which it is safe to spend in different parts of the mine and consider whether the risk is sufficiently close to the limit to make it advisable to wear personal radon monitors.

Radon exposure is dominated by the exposure received deep in the mine at the dig face. Bearing in mind the values above, it was recommended to industrial archaeologists that the time spent at the dig face of an untested mine should be restricted to 4 h each month. This time restriction ensures that the annual dose would only approach 6 mSv if the person was exposed to an annual average radon level of $16\,000 \text{ Bq m}^{-3}$ at the dig face. This recommendation would be valid for cave systems as well, as a comprehensive review by Field (2007) indicates that only a few cave systems exceed this value. It was also recommended that volunteers should wear personal radon dosimeters for a month at a time, so that

the dose could be monitored throughout the year. It would seem prudent to extend this recommendation to any cave or mine in the UK as well as for the locations in this study.

7 Conclusions

This research is ongoing and work is under way to map more mines in the Lake District with the aid of CATMHS. The variation in radon levels between and within such abandoned mines needs to be adequately modelled if accurate exposure data is to be derived. Future work will also look in more detail at seasonal radon variability and meteorological conditions within the Lake District mines and other similar systems.

However, the research so far clearly shows that radon levels in abandoned mines are not closely correlated to radon levels in the nearby built environment, since mines with high radon levels have been found in areas designated as having low radon potential, and the potential for raised radon levels in any newly discovered mine needs to be considered as it has the potential of being a significant risk to groups such as Archaeologists spending time in the mines. This paper proposes a time limit of 4 h per month in any mine where radon levels are unknown, and an initial summertime assessment of radon levels using track etch detectors exposed over one to three months. Once this has been done, a more appropriate time restriction can be proposed and personal radon monitoring considered if radon levels are high.

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