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AU9918824

Radon in an underground cave system in Victoria

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ABSTRACT:

Radon levels in a cave system in Victoria have been measured. The variation of radon and radon progeny levels with time, position throughout the cave and season have been determined. The radiation exposure of tour guides were estimated. The data is being used to develop a radiation management plan for the tour guides.

KEY WORDS:

Radon, progeny, equilibrium fraction, radiation dose, caves, tour guides.

INTRODUCTION:

Radon (^{222}Rn) is a radioactive gas formed as part of the decay chain of naturally occurring ^{238}U. Elevated levels of radon and its decay progeny have been linked with increased risk of lung cancer[1,2]. In the outside atmosphere or well ventilated indoor environments radon and its progeny present little health risk due to low concentration. However, in enclosed and poorly ventilated areas radon and radon progeny levels can build up. These types of conditions frequently exist in cave systems. Where such caves are used as tourist attractions, tour guides working in the caves can receive significant radiation exposure. Reducing the radon exposure of cave staff through increasing cave ventilation is not possible without disturbing the cave environment. Solomon et al.[3] carried out an initial assessment of radon levels in caves throughout Australia using time integrating radon measurement methods (CR-39 alpha-track detectors) over periods of three and twelve months. The study highlighted several caves in Australia where the average concentration of radon exceeded the action level of 1000 $Bq.m^{-3}$ as recommended by the National Health and Medical Research Council (NHMRC) and the National Occupational Health and Safety Commission[4] (NOHSC). The caves system at Buchan, Victoria, approximately 450 km east of Melbourne was shown to be one of these problematic systems, with the radon levels exceeding the action level for all measurement sites. Solomon et al. estimated that the effective doses to the tour guides in Buchan Caves were in the range of 5.1 to 8.9 mSv per annum[3].

Exposure to radiation in the workplace in the state of Victoria is controlled through legislation[5,6]. However, at present, the definition of radioactive substance in this legislation does not cover radon. Under the Occupational Health and Safety Act[7], administered in Victoria by the Workcover Authority, the employer has a general duty of care to provide and maintain as far as practicable a working environment that is safe and without risks to health. The NOHSC national standard provides guidance on how Workcover would expect employers to meet that duty of care in relation to ionizing radiation. Among other things, the NOHSC standard requires that employers demonstrate that the doses estimated to have been received by employees comply with the dose limits specified in the standard. A radiation protection program for cave staff will therefore involve quantifying the radon exposure of the staff through either personal monitoring, or area monitoring in the caves combined with detailed records of the time staff spend in the caves.

The aim of this study was to carry out further detailed monitoring of the radon in Buchan Caves, as recommended by Solomon et al.[3]. More specifically, the aim was to measure seasonal, diurnal and spatial variation in radon and radon progeny levels throughout the caves at Buchan, and to calculate the equilibrium fraction (F_r) throughout the caves. An accurate value of F_r is required to convert radon levels in caves into an effective dose. These measurements should allow a more accurate estimation of annual effective doses received by cave guides than was possible by Solomon et al. In addition a trial requiring four employees to wear a radon dosimeter (CR-39 badge) has been carried out. The data will be used in developing a radiation management plan for the management of Buchan Caves.

MATERIALS AND METHODS:

Radon concentration as a function of time was measured using a Genitron Instruments[8] ALPHAGUARD PQ 2000 monitor. This monitor is electrostatic in nature and takes continuous radon measurements which are integrated every ten minutes. The ALPHAGUARD monitor also simultaneously measures environmental variables such as relative humidity, air pressure and temperature. The first 50 minutes of radon measurements were discarded in calculations to allow for stabilisation of radon diffusion into the monitor.

Radon progeny concentrations were measured using two different types of radon progeny detectors. In one system, an automated monitor developed by the Australian Radiation Laboratory was used. Radon progeny were collected on a glass fibre filter paper using a small personal air pump. Continuous alpha decay counts of the radon progeny on the filter paper were taken using a solid state alpha detector. A count time of ten minutes was used before the alpha count number was logged, cleared and started afresh using a data logger. The second radon progeny monitor was incorporated into the ALPHAGUARD monitor. This detector was obtained half way through the collection of data reported in this paper. The two progeny detectors were calibrated using the radon chamber at the Australian Radiation Laboratory.

The radon progeny levels were calculated using the following formula:

$$PAEC = (C \times 7.2)/(\varepsilon \times F \times 1.3 \times 10^5) \text{ in Working Levels}^9.$$

where:

PAEC = potential alpha energy concentration in air;
C = alpha counts per minute;
ε = efficiency of the alpha detector; and
F = air flow rate through the filter paper.

The 7.2 factor is the average alpha energy from the disintegration of the radon progeny. The 1.3×10^5 factor converts the PAEC from MeV/litre into working level (WL).

As it takes about three hours for radon progeny to reach in-growth equilibrium, the radon progeny data collected for the first three hours at each particular location was not used in calculating the equilibrium fraction.

Measurement sites

Two caves at Buchan were being used for tourist purposes at the time of the study: Fairy Cave and Royal Cave. The two caves form part of a single system: it is possible to crawl from the exit end of the Fairy Cave to the entrance end of the Royal Cave. Measurement sites within the two caves were chosen as places of special interest where guides would halt a tour to allow observation or photography. The radon at these sites contribute the major part of any dose received by the guides due to radon in the caves. The location of the six sites in Fairy Cave and seven sites in Royal Cave are shown schematically in figure 1.

Measurement of diurnal variation

Diurnal variation in radon concentrations at Buchan Caves was measured during the summer of 1996-97 and winter of 1997. The ALPHAGUARD monitor was left at 13 sites for approximately 48 hours during summer, and at 11 sites for approximately 24 hours during winter. The shorter measurement periods during winter were a result of time constraints.

While the ALPHAGUARD monitor measured cave environmental variables such as relative humidity, air pressure, air speed and temperature within the cave at the measurement site, these variables were not measured outside the cave system at Buchan. The Bureau of Meteorology measure these variables at the town of Orbost, approximately 50 km east of Buchan. There may have been some variation in the values of environmental variables between Orbost and Buchan although overall trends are expected to be similar. These measurements were taken four times a day; at 3:00 a.m., 9:00 a.m., 3:00 p.m. and 6:00 p.m. local time.

Measurement of seasonal and yearly variation

Five field trips of 4 or 5 days duration were made to Buchan to measure radon and radon progeny concentrations: summer 1996-97, autumn 1997, winter 1997, spring 1997, and summer 1997-98. Up to seven sites in Royal Cave and six sites in Fairy Cave were measured each field trip. Measurements at each site were made for a period of at least 4 hours.

Measurement of local spatial variation

Initially, with only one radon monitor and one radon progeny monitor available, it was only possible to measure radon and progeny values in one position at each site. This position was about 20 cm above the floor of the cave. Later in the study, a second radon and radon progeny monitor were obtained, allowing measurement of the local spatial distribution of radon levels. Measurements were taken during spring 1997 with one set of radon and progeny detectors located about 20 cm above the floor of the cave, whilst the other set was located at least 60 cm from the wall or floor of the cave. Measurements at each site were made for a period of at least 4 hours.

Personal Dosimeters

The Australian Radiation Laboratory has developed a personal dosimeter for measuring radon levels. The dosimeter utilises CR-39, and the dosimeter housing is approximately 5 cm in diameter. The tour guides have placed the dosimeters in their shirt pockets whilst in the cave. The current wearing period is three months. A control dosimeter has been stored in the managers office. The dosimeters only became available in July 1997, so dosimeter data is only available for two wearing periods.

RESULTS:

Diurnal variation in radon concentration

The results of the diurnal radon concentration measurements are presented figure 2. The highest radon concentration measured was 9664 $Bq.m^{-3}$ at the Eastern Chamber during January (mid summer) in 1997. During summer months nearly all the sites showed some form of periodic diurnal variation in radon concentration. An example of the diurnal variation in radon concentration during summer is shown in figure 3. There was a correlation in trends between radon concentration and external temperature for most sites showing diurnal variation, although no quantitative relationship could be made as the external temperature readings were made at Orbost, a town 50 km distant from Buchan.

During winter months no sites showed diurnal variation in radon concentration. An example of the lack of diurnal variation in radon concentration during winter is shown in figure 3.

The ratio of the 9 a.m. to 5 p.m. average radon concentration and the 24 hour radon concentration for all locations were in the range 0.94 to 1.13 as shown in table 1. The average of the ratios was 1.00.

Environmental variables within the caves were very stable. Average temperatures at all sites within the caves were between 15 to 20 degrees Celsius. The temperature at each particular site remained extremely stable, showing less than 1 degree variation over several days. Similarly, air pressure and relative humidity remained extremely stable within the caves.

Seasonal variation

The results of the seasonal average radon and progeny concentrations, and working level measurements are detailed in table 2 and figures 4a, 4b, and 4c. The largest value of seasonal average radon concentration was 6871 $Bq.m^{-3}$ at the Octopus Chamber in Royal Cave during summer in 1997-98, the smallest value was 964 $Bq.m^{-3}$ at the Blackwood Chamber in Fairy Cave during winter in 1997. Average radon concentrations were considerably higher in summer than in winter for all sites, with spring and autumn values between the two extremes. While Fairy Cave showed a spread of average radon concentration values at all sites over the four seasons, the Royal Cave showed a relatively constant value of around 2000 $Bq.m^{-3}$ during autumn, winter and spring, but during summer the average concentrations rose to more than double this value.

Seasonal average progeny concentrations were more varied, with some sites showing higher values during the cooler seasons. The largest value of seasonal average potential alpha energy concentration (PAEC) was 0.70 Working Levels (WL) at the Ivory Palace in Fairy Cave during summer in 1997-98, the smallest value was 0.05 WL at the Reed Chamber in Royal Cave during autumn in 1997.

The difference in seasonal trends between average radon and progeny concentrations meant that average equilibrium fractions (F_r) were widely distributed from season to season, even at the same site. Values ranged between 0.59 at the Grand Terrace in Royal Cave during winter to 0.10 at the Reed Chamber, also in the Royal Cave, during both autumn 1997 and summer 1997-98.

Year to year variation

The radon levels have been measured during summer 1995-96 by Solomon et al.[3], and during summer 1996-97 and 1997-98 as part of this study. The data is presented in table 2 and figure 4. Radon levels measured during summer 1995-96 were comparable to the levels measured during 1996-97. Radon levels measured during summer 1997-98 was up to a factor of two higher than the levels measured during 1996-97.

In general, the radon concentrations measured in this study have been higher than the levels measured by Solomon et al.

Radon progeny levels was only measured in one location for both summers in this study. Radon progeny levels during summer 1997-98 are approximately double the levels measured in summer 1996-97.

Spatial variation

Figures 4a, 4b, and 4c demonstrate the obvious variation in seasonal average radon and progeny concentrations between different sites in the caves. Generally, sites closer to the entrance and exit of the caves showed lower seasonal average radon and progeny concentrations than sites situated towards the middle of the caves.

Results for radon and progeny concentration measurements of spatial variation with height from the floor of a particular site are shown in table 3. Radon concentrations were approximately the same for both levels at all sites. All sites showed increased radon progeny levels, and therefore equilibrium fraction, for measurements taken 20 cm from the cave floor compared to measurements taken 60 cm from the cave floor. Sites within Fairy Cave had a greater difference between progeny levels for the two heights than Royal Cave sites.

It should be noted that all other measurements in this study were made approximately 20 cm from the cave floor.

Tour guide dose calculation

The effective dose has been estimated for four tour guides. The tour guides have been required to keep records of the time spent in the caves during the study period. An estimate of the radon exposure (Radon concentration × Number of hours in caves) and the effective dose to the tour guides is presented in table 4.

Two methods have been used to estimate the exposure and the dose. The calculated exposure uses data collected during this study. It has been determined by taking the product of the average radon concentration at each cave location and the number of hours that each tour guide has spent at each location. The measured exposure has been determined from the radon dosimeters supplied by ARL. In general the radon exposure data is comparable.

The calculated effective dose also uses data collected during this study. It has been determined by firstly calculating the potential alpha energy concentration (PAEC) measured in Working Level Months (WLM) and then multiplying this value by the ICRP dose conversion factor of 5 mSv/WLM[10]. The PAEC was calculated by taking the product of the average radon progeny concentration at each cave location and the number of hours that each tour guide has spent at each location. In the calculation a year is taken to involve 2000 working hours, and so a factor of 167 working hours per month is used to convert hours to months in the cave. The measured effective dose has been determined from the radon dosimeters supplied by the Australian Radiation Laboratory (ARL). ARL has used a dose conversion factor of 5.5 $\mu Sv/(kBq.h/m^3)$[11].

This dose conversion factor has been estimated following measurements of particle sizes within Buchan Caves, and is more appropriate than the ICRP recommended value of 3.1 μSv/(kBq.h/m^3).

From table 4, the most exposed tour guide is receiving less than 1 mSv in 6 months, irrespective of which method is used to determine dose. As the busiest time for the tour guides is January, and as the radon levels are higher in summer than the other months, the radon exposure and dose to the tour guides is expected to be higher in the remaining six months of the year. Nevertheless, it is anticipated that the doses to the tour guides will be considerably less than the 5 mSv, and considerably less than the doses estimated by Solomon et al. The main reason for this is that the number of hours worked by the tour guides are considerably less than the times given to Solomon et al. In addition, the tour guide who spends the greatest amount of time in the caves, particularly for maintenance reasons, has not participated in the trial of the radon dosimeters. It has been estimated that this tour guide may spend up to two times the amount of time that guide 1 (see table 4) spent in the cave system in the past 6 months.

DISCUSSION:

The results of this study have shown that there are large variations in radon and radon progeny concentrations, and equilibrium fractions, within the caves.

Radon concentration within a cave system depends to a large extent upon the rate of air exchange with the outside. Cave ventilation is the single most important factor in determining if there is diurnal variation in the radon concentrations.

Consistently lower radon concentrations and a lack of diurnal variation during winter months have been measured within the Buchan Caves, as opposed to higher average radon concentrations with most sites displaying diurnal variation during summer months. Environmental variables within the caves, including air temperature, were found to be very consistent and stable over time. A qualitative relationship between radon concentration and external air temperature was also found. These results imply that the difference in temperature between the cave air and the outside air is an important factor in the overall trend of radon concentration within the caves.

Air temperatures at all measurement sites within the caves remained stable and between 15 to 20 degrees Celsius year round. While a simplistic explanation, when the outside air temperature was warmer than the cave air temperature, the cooler and denser cave air remained stagnant within the cave allowing radon levels to build up. Conversely, when the outside air temperature dropped below the cave air temperature the warmer cave air was exhaled from the cave and there was an influx of cooler air from outside, lowering the radon concentration in the cave. During winter months the internal cave temperatures were consistently warmer than the external air temperature which had an average maximum daily temperature of 15 degrees (measured at Orbost). This resulted in continual exhalation of warm cave air and influx of ouside air, little or no diurnal variation, and a lower overall radon concentration than during the summer months.

During summer months the internal cave air temperature may have been cooler than the outside air temperature during the day, but warmer than the outside air temperature during the night, leading to a periodic raising and lowering in the radon concentration.

CONCLUDING REMARKS:

Considerable variations in radon and radon progeny levels with position, with time of day, with season, and with year have been observed. The equilibrium fraction also varied considerably with position in cave and the season. Estimates of the effective doses to tour guides have been made. A radiation management plan for the tour guides at Buchan Caves will be developed.

ACKNOWLEDGMENTS:

The authors wish to thank the staff at Buchan Caves, in particular, Alan Oldroyd, Dale Calnin and Robyn Calnin, for their cooperation and assistance in the collection of the data.

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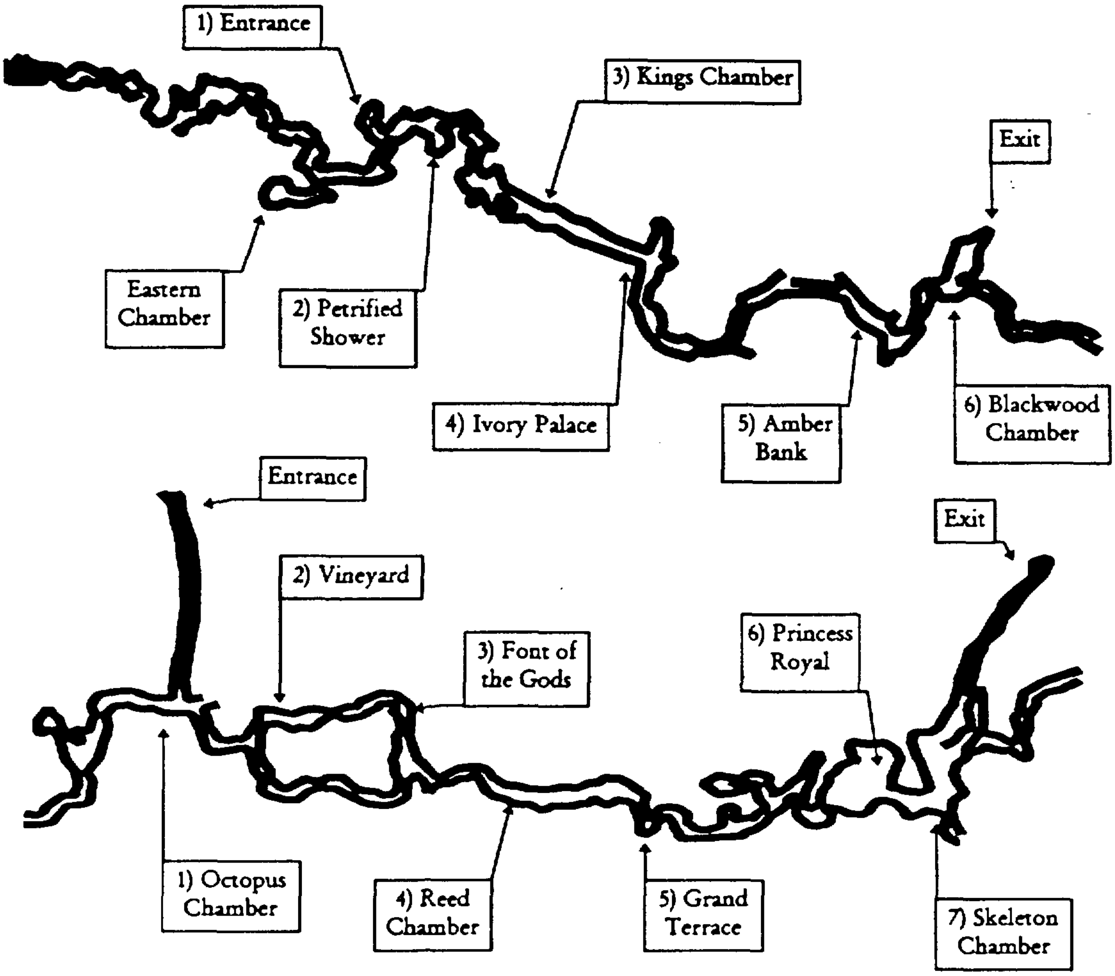

Figure 1: Maps of Fairy Cave (top) and Royal Cave (bottom) at Buchan, Victoria, showing the approximate location of measurement sites (numbered) and the entrances and exits. The two cave systems are connected, from the exit end of Fairy Cave and the entrance end of Royal Cave. It is possible to crawl from Blackwood Chamber in Fairy Cave to Octopus Chamber in Royal Cave.

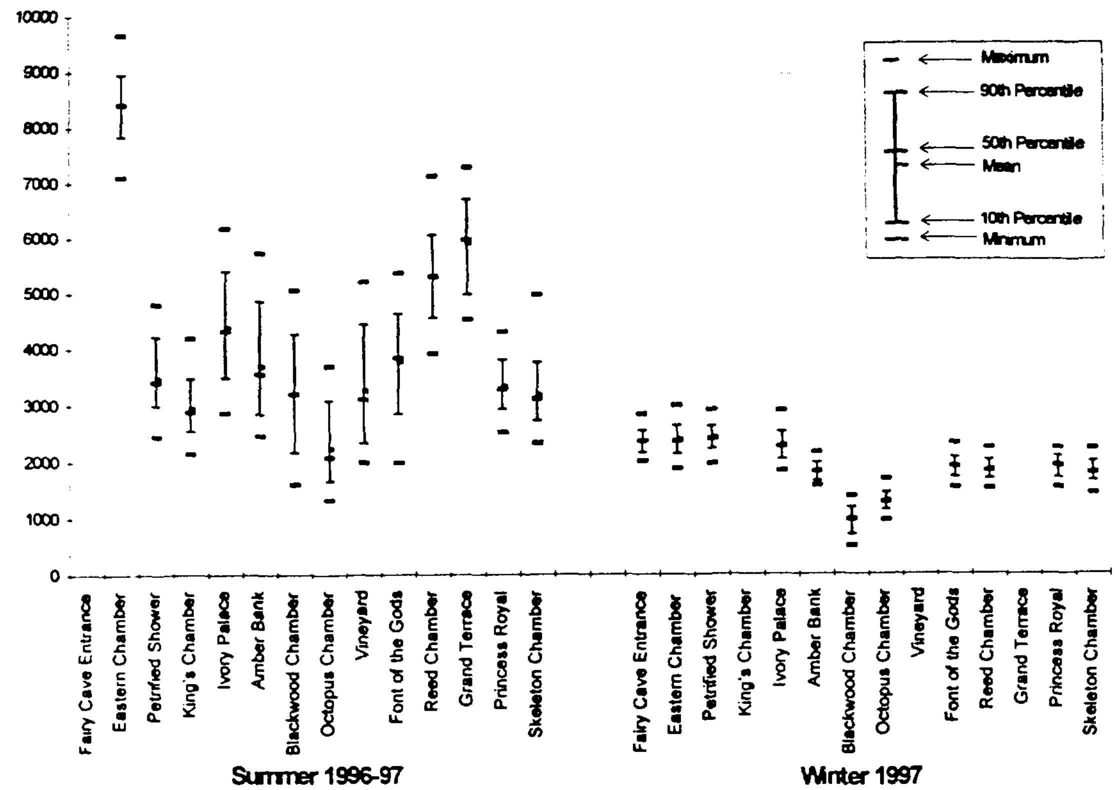

Figure 2: Range of variation in radon concentration during summer 1996-97 and winter 1997 for the Royal and Fairy Caves, Buchan.

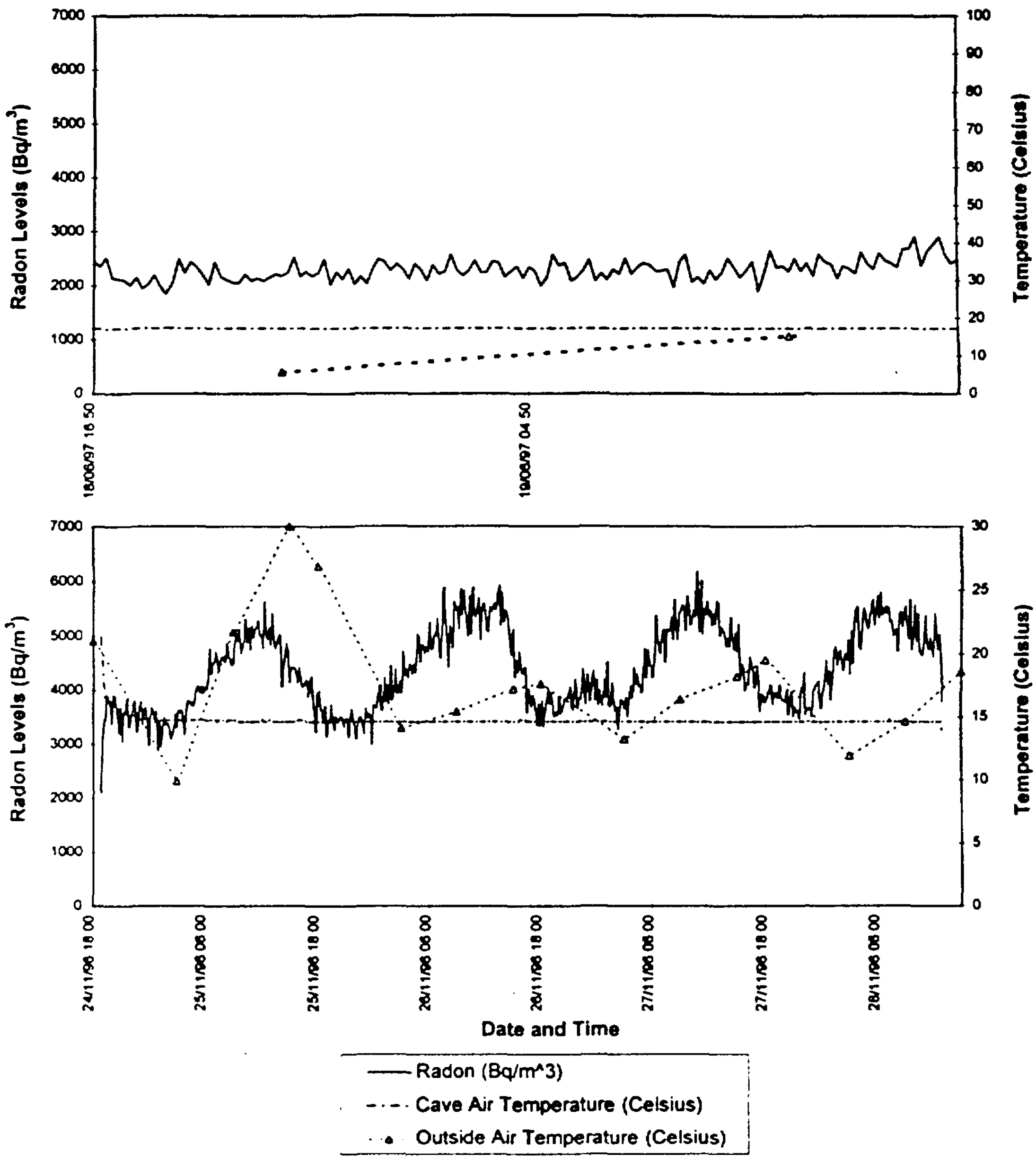

Figure 3: Diurnal variation of radon concentration and temperature during winter 1997 (top diagram) and summer 1996-97 (bottom diagram) in the Ivory Palace site, Fairy Cave. Note that the two diagrams are of different time scales, and that the top diagram only has the daily maximum and minimum outside temperature. All outside temperatures are for the town of Orbost, approximately 50 km from Buchan.

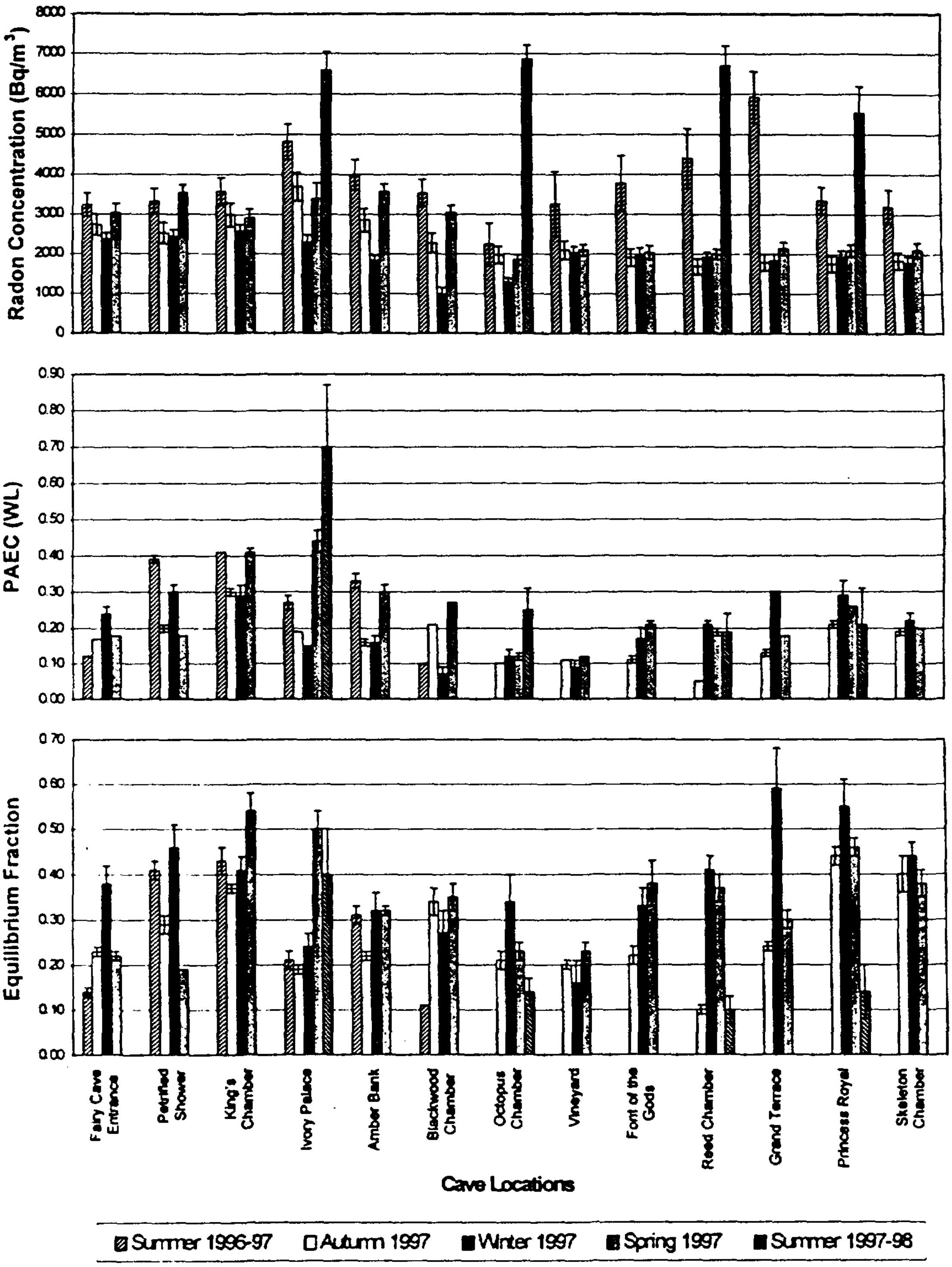

Figure 4a: Seasonal variation of average radon concentration for Buchan Caves (top).
Figure 4b: Seasonal variation of average potential alpha energy concentration (PAEC) for Buchan Caves (middle).
Figure 4c: Seasonal variation of average equilibrium ratios for Buchan Caves (bottom).

Site Name	Summer 1996-97			Winter 1997			Summer 1997-98		
	Radon concen-tration. 24 hour average (Bq.m^{-3})	Radon concen-tration. 9 AM to 5 PM average (Bq.m^{-3})	Ratio of 9-5 average to 24 hr average	Radon concen-tration. 24 hour average (Bq.m^{-3})	Radon concen-tration. 9 AM to 5 PM average (Bq.m^{-3})	Ratio of 9-5 average to 24 hr average	Radon concen-tration. 24 hour average (Bq.m^{-3})	Radon concen-tration. 9 AM to 5 PM average (Bq.m^{-3})	Ratio of 9-5 average to 24 hr average
Fairy Cave Entrance				2367 ± 161	2382 ± 176	1.01			
Eastern Chamber	8409 ± 423	8355 ± 395	0.99	2394 ± 200	2345 ± 175	0.98			
Petrified Shower	3481 ± 457	3393 ± 420	0.97	2428 ± 177	2435 ± 164	1.00			
King's Chamber	2944 ± 376	3002 ± 472	1.02						
Ivory Palace	4388 ± 737	4976 ± 522	1.13	2290 ± 197	2402 ± 218	1.05	6581 ± 466	6520 ± 369	0.99
Amber Bank	3696 ± 737	3888 ± 716	1.05	1834 ± 125					
Blackwood Chamber	3207 ± 769	3004 ± 744	0.94	964 ± 190	1057 ± 156	1.10			
Octopus Chamber	2238 ± 539	2390 ± 486	1.07	1298 ± 108			6871 ± 343	6876 ± 354	1.00
Vineyard	3259 ± 814	3081 ± 875	0.95						
Font of the Gods	3774 ± 694	3618 ± 717	0.96	1912 ± 146	1957 ± 174	1.02			
Reed Chamber	5308 ± 584	5324 ± 624	1.00	1859 ± 139	1897 ± 150	1.02	6708 ± 494	6626 ± 595	0.99
Grand Terrace	5920 ± 527	5800 ± 515	0.98						
Princess Royal	3346 ± 340	3257 ± 342	0.97	1934 ± 157			5527 ± 662	5688 ± 643	1.03
Skeleton Chamber	3188 ± 424	3183 ± 479	1.00	1813 ± 141	1766 ± 150	0.97			

Table 1: Summary of the Radon measurement results for summer 1996-97 and winter 1997 in Fairy and Royal Caves, Buchan, Victoria. The uncertainties shown are ± one standard deviation.

Season	Measurement	Cave Entrance	Eastern Chamber	Petrified Shower	King's Chamber	Ivory Palace	Amber Bank	Blackwood Chamber	Octopus Chamber	Vineyard	Font of the Gods	Reed Chamber	Grand Terrace	Princess Royal (Head Level)	Princess Royal (Ground Level)	Skeleton Chamber
SUMMER 1996-97	Average Radon concentration (Bq m-3)	3231 ± 189	8408 ± 423	3321 ± 243	3587 ± 255	4818 ± 380	3982 ± 281	3538 ± 204	2238 ± 539	3258 ± 814	3774 ± 884	4401 ± 745	5820 ± 840		3348 ± 340	3188 ± 424
	Average PAEC (WL)	0.12 ± 0.00		0.39 ± 0.01	0.41 ± 0.00	0.27 ± 0.02	0.33 ± 0.02	0.10 ± 0.00								
	Equilibrium Factor, F	0.14 ± 0.01		0.41 ± 0.02	0.43 ± 0.03	0.21 ± 0.02	0.31 ± 0.02	0.11 ± 0.00								
	Summer average radon concentration (ARL, 1998) (Bq m-3)	3772	3188	2353	1740	4588		3808		4572	4132	291			4123	2488
AUTUMN 1997	Average Radon concentration (Bq m-3)	2729 ± 135		2515 ± 211	2981 ± 229	3080 ± 215	2847 ± 239	2271 ± 175	1970 ± 181	2082 ± 113	1903 ± 167	1664 ± 132	1790 ± 149	1695 ± 115	1758 ± 137	1835 ± 138
	Average PAEC (WL)	0.17 ± 0.00		0.20 ± 0.01	0.30 ± 0.01	0.19 ± 0.00	0.16 ± 0.01	0.21 ± 0.00	0.10 ± 0.00	0.11 ± 0.00	0.11 ± 0.01	0.05 ± 0.00	0.13 ± 0.01	0.28 ± 0.01	0.21 ± 0.01	0.19 ± 0.01
	Equilibrium Factor, F	0.23 ± 0.01		0.29 ± 0.02	0.37 ± 0.01	0.19 ± 0.01	0.22 ± 0.01	0.34 ± 0.03	0.21 ± 0.02	0.20 ± 0.01	0.22 ± 0.02	0.10 ± 0.01	0.24 ± 0.01	0.58 ± 0.06	0.44 ± 0.02	0.40 ± 0.04
	Autumn average radon concentration (ARL, 1998) (Bq m-3)	730	2264	1191	1132	1870		1338		343	1110	774			439	1256
WINTER 1997	Average Radon concentration (Bq m-3)	2388 ± 161	2394 ± 183	2428 ± 177	2578 ± 168	2297 ± 187	1834 ± 125	984 ± 190	1278 ± 108	2028 ± 182	1974 ± 171	1913 ± 127	1828 ± 187		1934 ± 157	1778 ± 161
	Average PAEC (WL)	0.24 ± 0.02	0.24 ± 0.02	0.30 ± 0.03	0.29 ± 0.00	0.15 ± 0.02	0.16 ± 0.02	0.07 ± 0.02	0.12 ± 0.02	0.09 ± 0.03	0.17 ± 0.01	0.21 ± 0.00	0.30 ± 0.04		0.29 ± 0.02	0.22 ± 0.00
	Equilibrium Factor, F	0.38 ± 0.04	0.37 ± 0.03	0.48 ± 0.05	0.41 ± 0.03	0.24 ± 0.03	0.32 ± 0.04	0.27 ± 0.08	0.34 ± 0.08	0.18 ± 0.06	0.33 ± 0.04	0.41 ± 0.03	0.58 ± 0.08		0.56 ± 0.08	0.44 ± 0.03
	Winter average radon concentration (ARL, 1998) (Bq m-3)	1393	3414	1332	1513	1675		1088		1278	1271	1291			1225	1282
SPRING 1997	Average Radon concentration (Bq m-3)	3030 ± 233		3637 ± 187	2908 ± 219	3398 ± 389	3578 ± 188	3048 ± 179	1858 ± 125	2108 ± 142	2033 ± 172	1985 ± 127	2131 ± 180		2088 ± 152	2087 ± 188
	Average PAEC (WL)	0.18 ± 0.00		0.18 ± 0.00	0.41 ± 0.01	0.44 ± 0.03	0.30 ± 0.02	0.27 ± 0.00	0.12 ± 0.01	0.12 ± 0.00	0.21 ± 0.01	0.19 ± 0.01	0.18 ± 0.00		0.28 ± 0.00	0.20 ± 0.00
	Equilibrium Factor, F	0.22 ± 0.01		0.19 ± 0.00	0.54 ± 0.04	0.50 ± 0.04	0.32 ± 0.01	0.35 ± 0.03	0.23 ± 0.02	0.23 ± 0.02	0.38 ± 0.05	0.37 ± 0.03	0.30 ± 0.02		0.48 ± 0.02	0.38 ± 0.03
	Spring average radon concentration (ARL, 1998) (Bq m-3)	2200	4883	1982	2362	2463		1905		1958	1811	1815			1869	1710
SUMMER 1997-98	Average Radon concentration (Bq m-3)					6581 ± 446			6871 ± 344			6706 ± 484			5527 ± 662	
	Average PAEC (WL)					0.70 ± 0.17			0.25 ± 0.08			0.19 ± 0.05			0.21 ± 0.10	
	Equilibrium Factor, F					0.40 ± 0.10			0.14 ± 0.03			0.10 ± 0.03			0.14 ± 0.08	
	Summer average radon concentration (ARL, 1998) (Bq m-3)															
	Yearly average radon concentration (ARL, 1998) (Bq m-3)	3238	3804	3034	2964	3336		2834		3098	3082	3102				2949

Table 2: Summary of the seasonal radon and progeny levels and equilibrium fractions for summer 1996-97, autumn 1997, winter 1997, spring 1997, and summer 1997-98. The uncertainties shown are ± one standard deviation.

Site Name	Average radon concentration, (Bq.m^{-3}) 20 cm	60 cm	Average radon progeny concentration, (WL) 20 cm	60 cm	Average equilibrium fraction, F_r 20 cm	60 cm
Fairy Cave Entrance	3030 ± 233	3144 ± 150	0.18 ± 0.00	0.11 ± 0.02	0.22 ± 0.01	0.13 ± 0.02
Petrified Shower	3537 ± 197	3487 ± 277	0.18 ± 0.00	0.19 ± 0.02	0.19 ± 0.00	0.21 ± 0.02
King's Chamber	2906 ± 219	2958 ± 245	0.41 ± 0.01	0.28 ± 0.02	0.54 ± 0.04	0.35 ± 0.03
Ivory Palace	3396 ± 399	3536 ± 354	0.44 ± 0.03	0.24 ± 0.03	0.50 ± 0.04	0.26 ± 0.05
Amber Bank	3576 ± 189	3677 ± 278	0.30 ± 0.02	0.16 ± 0.01	0.32 ± 0.01	0.17 ± 0.02
Blackwood Chamber	3048 ± 179	3184 ± 218	0.27 ± 0.00	0.17 ± 0.01	0.35 ± 0.03	0.21 ± 0.03
Octopus Chamber	1856 ± 125	1946 ± 193	0.12 ± 0.01	0.09 ± 0.01	0.23 ± 0.02	0.17 ± 0.04
Vineyard	2105 ± 142	2150 ± 199	0.12 ± 0.00	0.09 ± 0.00	0.23 ± 0.02	0.15 ± 0.01
Font of the Gods	2033 ± 172	2054 ± 132	0.21 ± 0.01	0.17 ± 0.01	0.38 ± 0.05	0.32 ± 0.04
Reed Chamber	1995 ± 127	2068 ± 133	0.19 ± 0.01	0.14 ± 0.01	0.37 ± 0.03	0.26 ± 0.03
Grand Terrace	2131 ± 160	2128 ± 179	0.18 ± 0.00	0.15 ± 0.02	0.30 ± 0.02	0.24 ± 0.02
Princess Royal	2086 ± 152	2093 ± 142	0.26 ± 0.00	0.18 ± 0.02	0.46 ± 0.02	0.31 ± 0.04
Skeleton Chamber	2097 ± 188	2097 ± 135	0.20 ± 0.00	0.15 ± 0.01	0.38 ± 0.03	0.27 ± 0.03

Table 3: Summary of the radon and progeny measurement results for two different heights above the cave floor, 20 cm and 60 cm. Measurements were made in spring 1996-97. The uncertainties shown are ± one standard deviation.

Cave Staff	July - September 1997 Calculated Exposure. kBq.h/m^3	Measured Exposure. (CR39 badges) kBq.h/m^3	Calculated Dose. µSv	Measured Dose. µSv	October - December 1997 Calculated Exposure. kBq.h/m^3	Measured Exposure. (CR39 badges) kBq.h/m^3	Calculated Dose. µSv	Measured Dose. µSv
Guide 1	189	83	573	460	219	62	416	340
Guide 2	70	65	213	360	78	76	188	420
Guide 3	27	34	85	190	100	56	220	310
Guide 4	54	61	156	340	70	31	137	170

Table 4: Radon exposures and doses received by four cave guides during the periods July to September and October to December, 1997.