Radon Studies in Jenolan Tourist Caves, New South Wales, Australia

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Radon studies have been carried out for the past ten years at the Jenolan Tourist Caves, New South Wales, Australia. Extensive clastic sediment deposits found within the cave system have been identified as being the major radon source. By grab sampling it has been shown that radon levels within the caves vary over a wide range both diurnally and seasonally as well as varying spatially. A number of sites have been continuously monitored for radon and radon progeny in order to determine the average conversion factor necessary to determine radiation doses from radon measurements. Because of the different times that the cave guides and maintenance workers spend at various locations in the caves it is impossible to calculate the dose they would receive from their work place using the data accumulated from grab or continuous in-situ sampling. Thus, in order to fulfil its duty of care, the Jenolan Caves management has instituted a badge program that provides a measure of personal exposure of the cave guides and maintenance workers. The methods, results and conclusions of a one-year study at Jenolan Caves will be used to illustrate the paper.

The Jenolan Caves are 110 km west of Sydney (Figure 1). These caves are one of Australia's most spectacular and well-known natural resources, and lie within the Blue Mountains World Heritage Area. They have an international reputation for their varied, numerous, and colourful speleothems.

Figure 1 Location of Jenolan Caves

In 1991, Basden and James (Lyons 1992) measured high levels of radon in sections of the tourist caves at Jenolan. In some instances these levels exceeded 1000 Bq m^{-3}, the environmental safety level for radon in the workplace (NH&MRC and NOHSC 1995); above this level, affected areas must be ventilated. Radon is hazardous because it is a radioactive gas that decays via alpha particle emission into products that are themselves radioactive as well as short lived.

As part of a more detailed survey, Solomon *et al*. (1995) concluded that the radon levels at Jenolan Caves were not hazardous to cave tourists but presented a possible health risk to cave workers.

Not wishing to ventilate the caves, yet needing to fulfil its duty of care to the cave guides and maintenance workers, the Jenolan Caves management supported a number of investigations into radon within the tourist caves. These studies proposed to determine the radon source, how it varies and what the variations depend upon, and whether there is a risk to cave workers at Jenolan Caves.

The source of radon within the caves at Jenolan was established as being the clastic sediments. These sediments are extensive and widely distributed throughout the caves and their associated passages. Furthermore, it was realised that there was no way in which the radon emission from the sediments could be controlled that would not also harm the caves.

A second study of grab sample and continuous measurements established the spatial distribution and seasonal variation of radon within the northern section of the Jenolan tourist caves (Figure 2). Not only were radon levels found to exceed 1000 Bq m^{-3} at some sites, usually those deep in the caves, they exceed that value in all seasons. The northern Jenolan caves are entered from the Grand Arch and it is in their far reaches that radon levels of over ten times the allowable level have been measured. High radon levels are experienced in the areas of cave containing sediments or with sediment in the nearby passages.

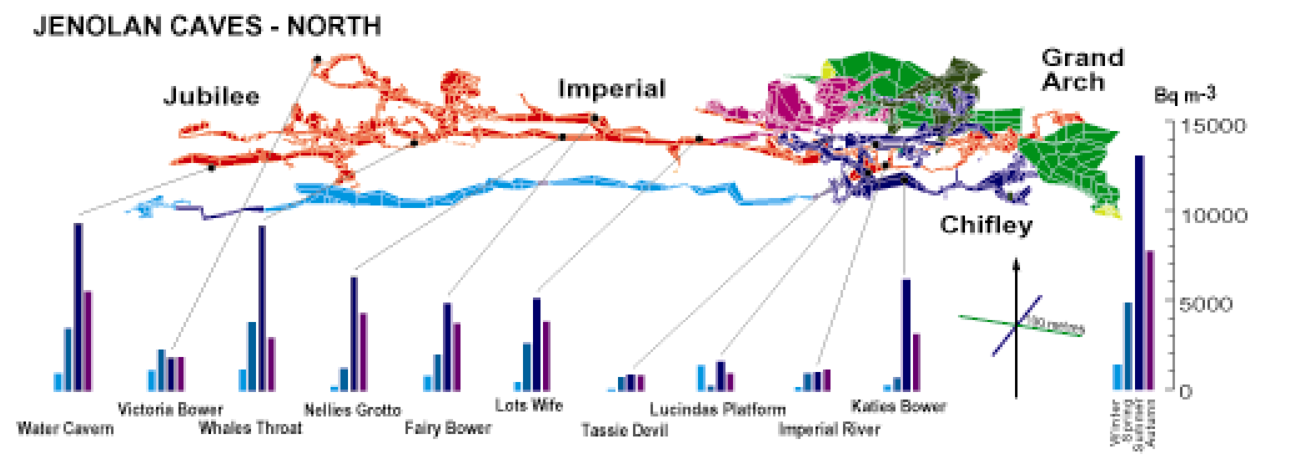

Figure 2 Distribution and Variation of Radon at Jenolan (N)

The diurnal variation during summer at the same sites (Figure 3) was also measured. Moreover, it was found that radon levels varied from year to year dependent upon climatic conditions. In addition, continuous measurements showed that on most days radon levels peak in early afternoon, corresponding with the time of peak usage.

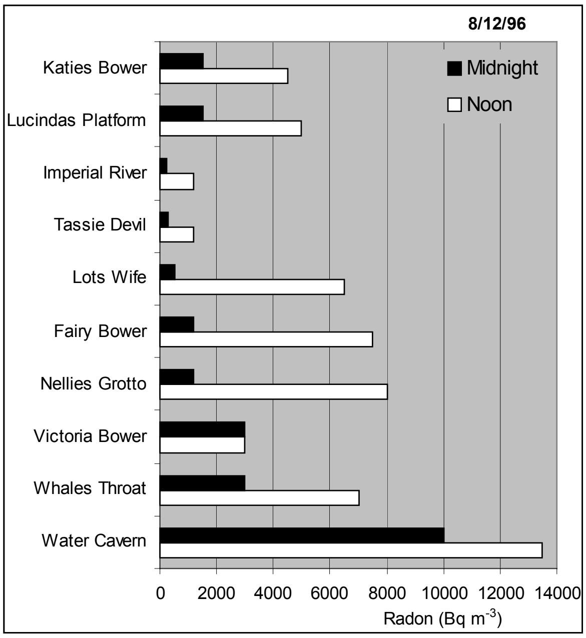

Figure 3 Diurnal variation of Radon

A contemporary study was aimed at determining whether to measure radon or its decay products (progeny) in order to assess the health risk at the caves due to exposure to radiation. Theoretically, the radon progeny should be measured as they present the greater health risk. Radon being an inert gas, is breathed into the lungs and out again. And, despite its short half-life of 3.8 days, the probability of it decaying whilst in the lungs is low. On the other hand, the progeny are chemically reactive, radioactive species of very short half-lives, in the order of minutes. If breathed in, there is a good possibility of reaction with the sensitive tissues of the respiratory tract and lungs, where they can become trapped, and where they can do the most damage. Furthermore, their own decay products are radioactive as well, and so enhance the hazard posed.

The progeny, however, may become attached to fine particles in the air, reducing their hazardous potential (Solomon *et al*. 1992, Solomon 2001). When attached to such particles, the progeny are referred to as "attached progeny". These fine particles and attached progeny are deposited in parts of the lung that have an effective cleaning mechanism, which can act to protect these sensitive tissues. The "unattached" progeny do not progress as far into the respiratory system. Although their momentum is the same, their speed of movement is much greater than that of the attached progeny, meaning they come into contact with the walls of the airways much earlier.

So, as an added complication, the hazard of the progeny depends on the proportion which are attached to particles. For instance, in an atmosphere with a given radon concentration and few fine particles, there will be a high proportion of unattached progeny, suggesting a significant hazard. But as unattached progeny interact with nearby surfaces more readily, the number of unattached progeny is reduced. This means, however, that there will be a lower total concentration of progeny in the air, but those that are there will be more hazardous.

Although the hazard is proportional to radon progeny concentration, measuring just the total concentration of progeny is an inaccurate measure of the hazard since the conversion factor varies according to the ventilation rate, fine particle size and concentration, as well as the detailed geometry of the immediate environment. In practice, it is usually more accurate and much simpler to estimate radiation exposure from radon concentration rather than from total radon progeny concentration.

In 1998, Zahorowski *et al* conducted an intensive 6 month survey of two chambers at Jenolan Caves, the results of which indicate that dose estimates based on the ICRP-65 convention (ICRP Publication 65, 1994) should be increased by 50% for these caves. The ICRP-65 convention was derived from radon and dose measurements from factories and homes. Caves, however, tend to have lower ventilation rates and lower particle concentrations than homes and this leads to a given radon concentration being more hazardous. Subsequent analysis by Zahorowski *et al* (1998) of a longer time series of data showed that a factor of 2 increase is necessary to allow for the special attributes of the cave atmosphere at Jenolan.

The conclusion reached at the end of these studies was that neither grab sampling nor continuous measurements of radon or its progeny were of use in establishing the level of health risk to an individual, particularly as these types of measurement are site-related. Consequently, such measurements cannot accurately estimate the exposure to an individual who moves between sites. Furthermore, any method of assessing the risk associated with exposure to radon-laden air is dependent upon the stability of the parameters under which the measurements are conducted. And, it has been shown at Jenolan that, over time, radon concentrations do not follow any predictable pattern. To overcome these problems, a reliable method of measuring personal exposure was needed.

There are two types of personal monitors: progeny monitors and radon badges. Radon progeny monitors are expensive - around US$10,000 per unit - and conspicuous. Although portable and computerised, they are also heavy, containing a large battery and air pump. The batteries need recharging on a daily basis and the on-board memory requires downloading to an external computer system for storage. They do have a considerable advantage in that the dose is immediately available but the reliability of that result depends upon the conversion factor utilised.

Radon badges are simpler and less expensive (~US$40) than progeny monitors, and require no power or computer back-up on-site. But, no instantaneous dose result is available, as the badge needs to be analysed in a laboratory.

Radon Badge Method

The personal radon monitors used at Jenolan consisted of a piece of TED[#] material in a permeable plastic container roughly 5 cm in diameter, conveniently and innocuously designed as a badge that clips onto clothing or a belt. These were provided to Jenolan Caves management by the Australian Radiation Protection and Nuclear Safety Agency (ARPNSA), who also analysed the TED material and produced the dosage reports. The guides and maintenance workers were required to wear the badges at all times at work, with a control kept in the Guides Office. Badges were kept in the same location as the control when not being worn. The guides and maintenance workers also kept journal records of the hours spent per day underground. Together the radon exposure measured by the badge, and the recorded hours underground, were used to determine the dose accumulated by the cave workers in the caves.

It was decided that, to avoid over exposure of the TED material, the badges should be analysed every 3 months and on a seasonal basis, corresponding to the same periods of measurement used in previous studies (eg. Figure 2). After 2 three-month periods, corresponding to summer and autumn, it was decided that a six-month exposure time over winter and spring would not lead to over exposure of the TEDs. A total of 20 badges were used (19 cave workers and a control). Although complete records of radon exposure were obtained, ten of the time keeping journals were incomplete due to periods of leave and turnover of staff.

Results and Discussion

The results of the badge program at Jenolan, conducted over several years, are shown in Figures 4, 5 and 6. Figure 4 shows the radon exposure for cave workers for the year 1999. As can be seen, no individual received a total exposure greater than 14 mSv. The allowable exposure limit for a "radiation worker" is 20 mSv per year averaged over 5 years (Solomon *et al*. 1996). The same graph also illustrates the seasonal variations that occur in the exposure, and endorses that radon levels are highest during summer as shown in Figure 2. There are clearly anomalies in the records shown in Figure 4, such as that of badge 18, which may be explained by the worker concerned being deployed in regions at the end of the cave system where the radon level is continuously high (Figure 2). No attempt has been made to link recorded level of exposure to site within the cave system.

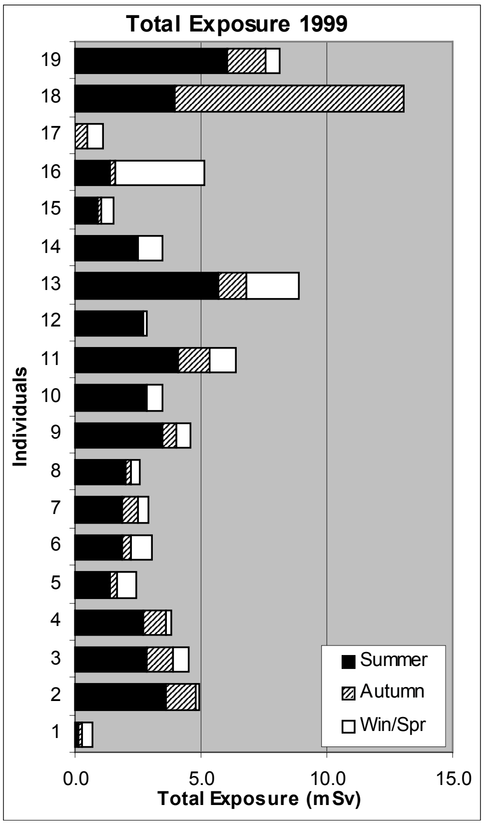

Figure 4 Measured Exposures by Badge Monitors

The management of the Jenolan Caves, after the publication of the Worksafe Report (Solomon *et al*. 1996) into occupational exposure to radon by cave workers, set a working limit of 1000 hours underground. Figure 5 extrapolates, for those cave workers where complete time keeping journals were available, the doses shown in Figure 4 to an estimated exposure for 1000 hours underground during 1999. The extrapolation was necessary because no cave worker at Jenolan Caves was underground for more than this time limit while at work. In this case, it is readily seen that no cave worker approached the limit set for a radiation worker (ie. 20 mSv), and only one individual exceeded half that limit.

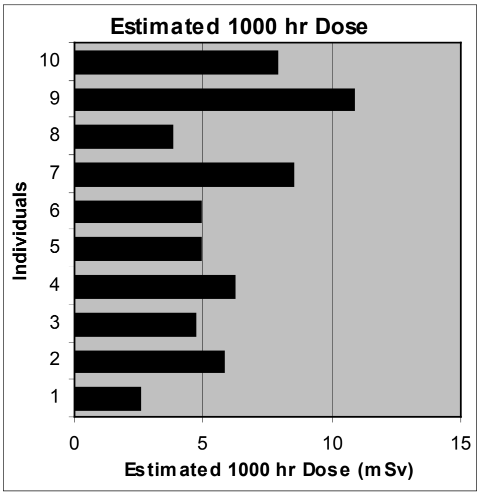

Figure 5 Estimated 1000 hour Exposure

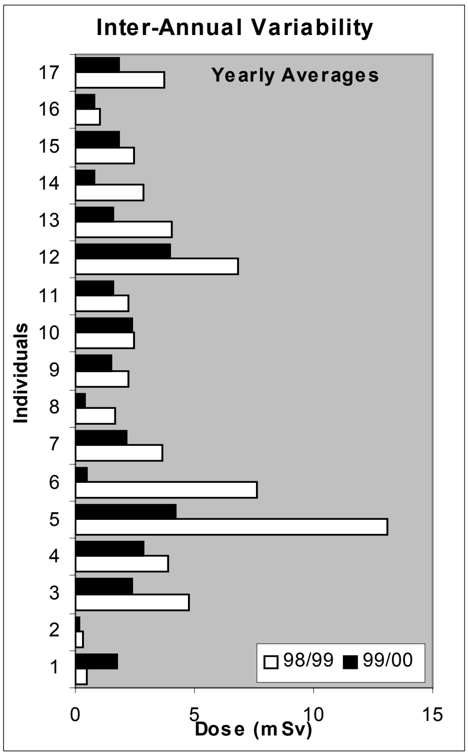

Figure 6 Yearly Variations in Dose Measurements

Figure 6 shows the variation that can occur in exposure measurements between two consecutive years, proving that regular exposure measurements need to be taken. From the graph, the radon exposure measured during the 1999-2000 period was considerably lower than that of the 1998-1999 period. This corresponds to very different climatic conditions experienced in those two years at Jenolan, illustrating further the unpredictability of the radon levels from year to year as well as season to season.

Conclusions

The studies of spatial, seasonal, diurnal and annual variation of radon at Jenolan Caves endorsed previous findings that there was no risk to tourists while also confirming that there could be a risk to cave workers. After careful consideration of a number of studies it was clear that the risk to cave workers could not be assessed from the site specific radon studies. Therefore, it was concluded that a badge program was needed to assess the risk to cave workers. Additional studies at Jenolan Caves led to the conclusion that it was preferable both scientifically and economically to use personal monitors that measured radon rather than radon progeny.

The badge program conducted at Jenolan Caves has successfully shown that, in the years 1998-2000, the health risk due to exposure to radon decay was not at a hazardous level. It confirmed that in environments such as caves the use of personal badges is necessary to properly assess any hazard due to radon. The badge program has shown that deployment of workers in the high radiation areas could conceivably lead to unacceptable doses. Although the badge program has only been in operation for 2 years, the results obtained indicate that the doses need to be monitored on a regular basis. Consequently, the management at Jenolan Caves has decided to continue the program.

Acknowledgments

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[#] Track etch detectors (TEDs) are film-like materials that are sensitive to impacts by alpha particles, and thus can record the decay of radon by exposure to radon-laden air. The TED needs to be analysed in the laboratory as an etching process is used to bring out the impact craters which are then counted.