AUSTRALIAN RADIATION LABORATORY

OCCUPATIONAL EXPOSURE TO RADON IN AUSTRALIAN TOURIST CAVES
AN AUSTRALIA-WIDE STUDY OF RADON LEVELS

FINAL REPORT
OF
WORKSAFE AUSTRALIA RESEARCH GRANT (93/0436)

by

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ABSTRACT

The study described in this report sets out to determine which Australian show caves have long-term radon levels in excess of the proposed action level of 1000 Bq m^{-3}. The collaborative study between the Australian Radiation Laboratory (ARL), the University of Sydney and the University of Auckland, was carried out with the support of a Research Grant from Worksafe Australia. The aims of this study were to measure radon levels for each season over a period of one year, at representative sites in all developed show caves around Australia, to determine yearly average radon levels for each cave tour, based on these site measurements, to estimate the radiation doses to the tour guides employed in these caves, and to identify caves with radon concentrations in excess of the action level.

The 12-month study of ^{222}Rn levels in Australian show caves was commenced in March 1994. Radon monitors were placed in representative sampling sites in 52 cave systems in 24 locations around Australia. The measurements were restricted to established show caves and a total of 286 sites were monitored. A pair of passive, integrating radon monitors based on CR-39 detectors were used to measure both 3-monthly, seasonal, as well as 12-monthly, annual radon levels at each site. The placement of most of these monitors required an initial visit to each cave location, but subsequent seasonal changeovers were carried out by mail and required the close cooperation of the tour guides and cave management at each location. The exposure period for the monitors was May 1994 to June 1995. Information was obtained from all locations on the sequence and duration of each cave tour. This allowed for the radon levels to be weighted for the time spent at each sampling site during a tour in order to determine the time-weighted radon level for each show cave tour.

The values for the radon concentration at each monitoring site ranged from ambient (< 20 Bq m^{-3}), up to over 9000 Bq m^{-3}. There was marked seasonal variability at most measurement sites; the highest value was measured during the summer, but the following season the same site recorded a radon level close to 1000 Bq m^{-3}. Similar trends were found for spatial variations between sampling sites in some cave systems, with variations of more than a factor of 10 between some sites in the same cave system. This spatial variability tended to smooth out the range of values for the time-weighted radon levels for each cave tour. Of the 67 cave tours in this study, 14 tours had time-weighted yearly average radon levels in excess of 1000 Bq m^{-3}. Most of these caves were in New South Wales, Victoria and Tasmania. In this study, no show caves in South Australia, Queensland, Western Australia or the Northern Territory were in excess of the action level. Most of the cave managements provided work records for each tour guide at each location over the 12 month period of the measurements. The work records were combined with the measurements of the seasonal radon levels for each cave tour in order to estimate the integrated radon exposure to each tour guide. These integrated radon exposures were converted to radon progeny exposures assuming a single value of 0.4 for the radon equilibrium factor. The yearly radiation dose (annual effective dose) was calculated for 116 tour guides using the conversion convention recommended by the International Commission on Radiological Protection (ICRP). The estimated yearly radiation dose for 82 of these guides was less than 1 mSv, between 1 and 5 mSv for 30 guides, and between 5 and 10 mSv for the remaining 4 guides. The highest estimated radiation dose was 9 mSv per year, which is less than one half of the present recommended occupational limit for radiation exposure.

INTRODUCTION

In Australia, workplace exposure to radiation during the mining and milling of radioactive ores is tightly regulated and controlled to ensure minimal health detriment. Exposure in the workplace to environmental sources of radiation is usually excluded from these regulations. In its Publication 65 (ICRP, 1994a), the International Commission on Radiological Protection has produced guidelines and recommendations dealing with workplace exposure to elevated background radiation, in particular, the risk associated with the inhalation of radon and radon progeny. An action level for ^{222}Rn of 1000 Bq m^{-3} was proposed. The Australian National Health and Medical Research Council (NH&MRC) and the National Occupational Health and Safety Commission (NOH&SC) have prepared joint recommendations and standards based on the ICRP recommendations, for application in the Australian context (NH&MRC, 1995; NOHCS, 1995). Background information on radiation exposure from radon and radon progeny is provided in *Appendix I*.

Australia has over 60 tourist or show caves. Preliminary measurements in some of these caves have shown ^{222}Rn levels in excess of this proposed action level (Solomon, 1994). These ^{222}Rn levels, while posing no risk to members of the public viewing the caves, may present a potential long-term health risk for the full-time staff spending extended periods conducting tours or carrying out maintenance within the caves. In April 1992, at a meeting between radiation researchers and cave managers, a collaborative study programme was devised to assess the potential health hazard to employees at show caves around Australia.

To assess the magnitude of this potential risk, the Workshop proposed a 3-tier measurement programme:

- *Stage 1* of this programme proposed an Australia-wide study of all major tourist caves to identify those with high radon levels;
- *Stage 2*, those caves identified as containing high radon levels would be subjected to more detailed monitoring;
- *Stage 3* would require a full radiation risk assessment using sophisticated radiation monitoring equipment.

In early 1994 Worksafe Australia provided a Research Grant to fund a *Stage 1* collaborative study involving the Australian Radiation Laboratory (ARL), the University of Sydney and the University of Auckland, with the aim of carrying out an Australia-wide survey of radon levels in caves. There are thousands of caves in Australia. However, this grant was specifically for developed show caves employing staff for tours and cave maintenance. The caves in the study are under the management of various state departments, local authorities or private groups.

The aim of the present studies were:

- to measure radon levels for each season over a period of one year, at representative sites in all developed show caves around Australia;
- to determine yearly average radon levels for each cave tour, based on these site measurements;
- to estimate the radiation doses to the tour guides employed in these caves; and
- to identify caves with radon concentrations in excess of the action level

This report is a detailed description of the results of this collaborative study.

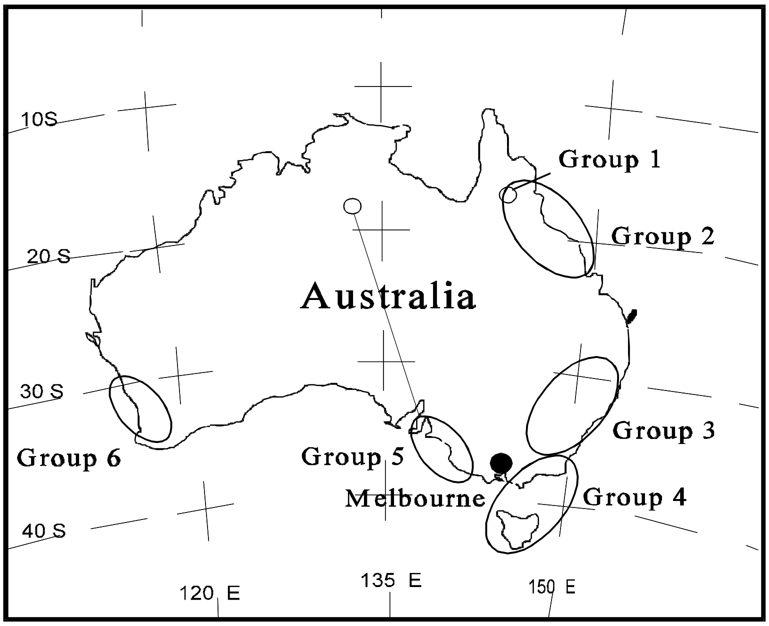
METHODS AND MATERIALS

The caves in the Worksafe study are grouped by location and listed in Table 1. The geographical distribution of the groups is shown in Fig. 1. Apart from the Undara Lava Tubes in Northern Queensland, which are formed in Paleozoic basalt flows, all of the caves monitored in this study have developed in carbonate rocks, usually limestone. However, they are widely disparate in age, developmental extent and the degree of their association with rocks of volcanic origin, which tend to be a greater source of radon.

TABLE 1. Developed show caves in Australia

GROUP	STATE	Location	Cave
GROUP 1	Queensland	Undara	*Undara Lava Tubes*
GROUP 2	Queensland	Chillagoe	*Royal, Trezkin*
		Rockhampton	*Johansens*
		Rockhampton	*Olsens, Cammoo*
GROUP 3	New South Wales	Abercombie	*Arch, Bushranger, Grove, King Solomons*
		Jenolan	*Chifley, Imperial, Jubilee, Orient, Baal, Lucas, River, Cerebus, Ribbon*
		Wombeyan	*Fig Tree, Wollondilly, Kooringa, Junction*
		Wee Jasper	*Careys*
		Wellington	*Cathedral, Gaden*
		Yarrangobilly	*Jillabanean, Jersey, North Glory, South Glory, Castle, Harry Woods*
GROUP 4	Victoria	Buchan	*Royal, Fairy*
		Murrindal	*Shades of Death*
	Tasmania	Mole Creek	*King Solomons Cave, Marakoopa*
		Hastings	*Newdegate*
		Gunns Plains	*Gunns Plains*
GROUP 5	Northern Territory	Cutta Cutta	*Cutta Cutta, Tindall*
	South Australia	Naracoorte	*Blanch, Alexandra, Victoria Fossil, Wet*
		Tantanoola	*Tantanoola*
		Kelly Hill	*Kelly Hill, Mount Taylor, K9*
	Victoria	Nelson	*Princess Margaret Rose*
GROUP 6	Western Australia	Yanchep	*Yanchep Crystal*
		Yallingup	*Yallingup*
		Margaret River	*Lake, Mammoth, Jewel, Moon*

Fig. 1 The geographical distribution of the major show caves within Australia, grouped by geographical location.



Workplace Agreements

The successful completion of this study has required close cooperation between the participating laboratories, the cave managements, the tour guides and the appropriate union bodies. The cooperation of the tour guides has been crucial to this study, since the collection and placement of all but the first round of monitors was the responsibility of the guides at each cave. Written workplace agreements for all sites were obtained from both management and tour guides, as well as all relevant union organisations. The study was granted Departmental Ethics Committee approval in February 1994 (Ethics Register Number : 94/ 0026).

Site Selection

For this study, passive radon monitors were required to be placed at representative sites in each cave, selected during a field visit to each location. Factors considered in site selection were:

- normal work practices within each cave, as determined from discussions with the guides and cave managements;
- previous on-site measurements of radon and radon progeny;
- careful assessment of the factors known to affect radon concentrations such as cave configuration, ventilation and the presence of sediments and different rock types.

Depending on size and complexity of each show cave, between 2 and 6 sites were designated. In all, a total of 286 sites were selected, providing measurements for more than 52 cave systems at 24 locations around Australia. A seven character site code based on the cave location, cave name and site was devised to identify each site. A full list of measurement sites, ordered by site code is in given in *Appendix II*. To facilitate the description of monitor placement, an attempt was made to obtain maps of each cave system under study. These maps were redrawn in a consistent and simplified way for entry into the site database. A compilation of these site maps is in given in *Appendix III*.

Two radon monitors were placed at each site; one was replaced at regular 3-monthly intervals to provide data on seasonal variability of radon levels, the other exposed for the full 12 month period to give annual average radon levels. At the end of each 3-month exposure period, new monitors were placed at each site and the exposed monitors were returned to ARL by mail for analysis. The monitors do not provide any information on diurnal variability of radon. However, when combined with information on employee work patterns, the seasonal and annual averages can be used to provide a preliminary estimate of the occupational radiation dose at each site.

Radon Measurement

The monitors used for the study were designed and fabricated at ARL. The detection material was CR-39 [(1)], a thermosetting homopolymer with the empirical formula $C_{12}H_{18}O_7$. For each monitor, a rectangular piece of CR-39 was located in the bottom of a polypropylene container. The lid of this container was screwed on to finger tightness during assembly, and it remained in place during the exposure. The diffusion time into the container was sufficiently large that there was no contribution to tracks on the CR-39 from ^{220}Rn (thoron). These radon monitors are identical to those used to carry out the survey of radon levels in Australian homes (Langroo et al., 1991).

After exposure the monitors were returned to ARL for analysis. The CR-39 detectors were etched using 6.25 M solution of analytic-grade potassium hydroxide at 70 ± 1 C. After etching for 6 h the CR-39 detectors were thoroughly rinsed with hot water until all the etchant was removed. The detectors were then air dried. Due to the high track densities on some of the CR-39 detectors, it was difficult to use automatic counting. Therefore, all detectors were manually read using an optical microscope connected to a videcom camera and television monitor. This system had a nominal magnification of X250. The total area scanned was 0.025 cm^2, comprising 30 separate areas, each 0.0008 cm^2.

ARL is a Reference Laboratory for the International Radon Metrology Programme and maintains a radon calibration facility at its laboratory in Melbourne. This facility was used to ensure proper calibration of the radon monitors, particularly for the high track densities at the higher integrated radon exposures. Standard monitors taken from the same sheet of CR-39 as the field monitors were exposed to known concentrations in the ARL radon chamber. These standards, as well as unexposed control monitors were then etched and readout with the corresponding batch of survey monitors. Nominal calibration factors were of the order 0.1 tracks cm^{-2} per (Bq m^{-3} d), with an average background track density of 60 tracks cm^{-2}.

Gamma-ray Measurement

Each monitor also contained a $CaSO_4$(Dy) thermoluminescent dosimeter (TLD) for the measurement of the external gamma-ray radiation. The TLD results, converted to effective dose are reported in *Appendix VI*, but no further analysis was made for this report.

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(1) Supplied by Pershore Moulding Ltd., Pershore, Worcestershire WR102DH, United Kingdom

DATA ANALYSIS

During the course of the radon measurements two further sets of data were collected for each cave location. Firstly, information was obtained on the normal times spent at each measurement site in the course of a typical cave tour. Each tour was allocated an identifying code based upon the cave location and tour name. The reported tour durations at each site are tabulated in *Appendix IV*, as a function of cave location and cave tour. The second data set comprised information on the total hours spent on each tour by each tour guide over the one year period of radon measurements. Where possible these work records were obtained for each month between June, 1994 and July, 1995. These values were then analysed to give seasonal work times for each tour guide. To preserve confidentiality, each tour guide was allocated a code based upon the cave location and a local identifier. In some case it was not possible to obtain detailed work records and the seasonal values were determined from the total yearly work hours, assuming equal time per season. A number of caves did not provide work records. The full work record data is tabulated in *Appendix V*. The initial analysis of the data was carried out using a series of linked PC-based database tables. A summary list of the content of these databases is given in Table 2.

Table 2. Summary of Databases produced by this Study

Database Name	Record Descriptions
Cave Specific	
WSCAVES.DB	Cave location, Show caves names, Cave Codes, State, Location map
WSLOCATN.DB	Cave Location, Contact Name, Organistaion, Address, Head Guide, Work Representative, Telephone, Fascimile
WSSITES.DB	Show Cave Name, Cave Site Code, Site Description, Site Map
Tour Specific	
WSTOURS.DB	Tour Code, Cave Location, Tour Name, Tour Duration
WSSEQU.DB	Show Cave Name, Tour Code, Cave Site Code, Sequence Number, Time Fraction
Tour Guide Specfic	
WSGCODES.DB	Cave Location, Guide ID, Guide Name
WSGUIDES.DB	Cave Location, Tour Code, Guide ID, Winter Work Hours, Spring Work Hours, Summer Work Hours, Autumn Work Hours
Measurement Specfic	
WSMONITR.DB	Monitor ID, Issue date, Etch data, Radon Exposure, TLD ID, TLD Readout, TLD Sensitivity, Gamma Value
WSMEAS.DB	Cave Site Code, Period, Monitor ID, Date In, Date Out, Radon Exposure, Gamma Value

Radon Exposure

For each cave tour and each season, the weighted radon concentration ${}_{season}[Rn]_{wghted}$ (in units of Bq m^{-3}) was derived from the data in WSMEAS.DB and WSSEQU.DB using the formula;

$$ {}_{season}[Rn]_{wghted} = \frac{\sum_{sites} {}_{season}[Rn]_{sites} * t_{site}}{\sum_{sites} t_{site}} $$

where ${}_{season}[Rn]_{site}$ is the measured concentration of radon at one site on the tour for a particular season, and t_{site} is the time spent at that site on the tour.

The radon exposure for each guide E_{guide} (in units of Bq m^{-3} h) was derived from the guide work hours for each season ${}_{season}t_{guide}$, taken from the database WSGUIDES.DB, and the weighted radon concentrtions for each tour and season as calculated above, using the equation

$$ E_{guide} = \sum_{season} \sum_{tour} {}_{guide}t_{tour} * {}_{season}[Rn]_{wghted} $$

Radon Progeny Exposure

The risk from exposure to radon is associated with the inhalation of the short-lived radon decay products (radon progeny). This present study measures only the long-term average of the parent radon. A full analysis of the tour guide radiation dose requires detailed information on degree of disequilibrium between radon and its progeny for each site and for each season. Previous detailed measurements of radon and radon progeny concentrations in one of the caves in this current study situated at Buchan, Victoria, (Solomon, 1992) had yielded values for the equilibrium ratios between 0.36 and 0.52, with an average of 0.4. In the absence of experimental data on equilibrium factors for the remaining caves in the study, this average value was used to derive an estimate of the radon progeny Potential Alpha Energy Concentration (PAEC) exposure W_{guide}, in units of Working Level Month (WLM), for each of the tour guides, using the formula;

$$ W_{guide} = \frac{E_{guide} * 0.4}{37 * 100 * 168} $$

(the SI unit for PAEC is J m^{-3}. One WLM is equivalent to 20.8 µJ m^{-3}.)

Radiation Dose

The PAEC exposure is a measure of the exposure to the airborne concentration of radon progeny. The radiation risk is related to the *effective dose* received by an individual from the inhalation of the radon progeny. This effective dose can be related to the PAEC exposure using dosimetric models of deposition of the radon progeny within the human respiratory tract (for example the ICRP Respiratory Tract Model (ICRP66, 1994b)), or it can be inferred from the results of epidemiological studies of lung cancer death amongst uranium miners. For this study, the ICRP *conversion convention* value of 5 mSv WLM^{-1} (ICRP 65, 1994a) was used. This value is based on the results of epidemiological studies, and assumes that the aerosol conditions for the exposure were not too different from those for the uranium miner exposures.

RESULTS

^{222}Rn Levels

The full 12-month exposure period were completed in June 1995. In general, the return rate for the exposed monitors was very good. Of the 1400 measurement sets there were problems with only 115 monitors. These problems varied from failure to place the monitors at the appropriate site, to missing or damaged CR-39 detectors. In some caves the damage to monitors was apparently due to rats. There were some inconsistencies between the seasonal and annual results. The measured concentrations ranged from close to ambient levels (< 20 Bq m^{-3}), up to the highest value of 9250 Bq m^{-3}. The full list of seasonal and annual measurement results for radon levels, together with the gamma-ray levels as determined from the TLD measurements, for each site in the study is given in *Appendix VI*.

The weighted radon concentrations for each cave tour were calculated from the site radon measurements and the tour times at each site. The seasonal results for ^{222}Rn levels, together with the 12-monthly averages, for each cave tour within each of the six Groups, are summarised in Tables 3-8. Of the 67 tours, 14 tours had weighted yearly averages in excess of 1000 Bq m^{-3}, with almost one half of the tours exceeding the action level located in Group 3. Table 9 summarises the seasonal results for ^{222}Rn levels for each tour, together with the 12-monthly averages for the above-ground offices at some locations.

TABLE 3. Seasonal and 12-monthly average [^{222}Rn] for caves tours in Group 1.

	^{222}Rn Level (Bq m^{-3})				
Tour Code	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
UND ARCH	23	290	498	173	246
UND BARKER	241	728	442	268	420
UND ROAD	108	212	190	190	175
UND WINDTUNNEL	68	25	43	43	45

TABLE 4. Seasonal and 12-monthly average [^{222}Rn] for caves tours in Group 2.

	^{222}Rn Level (Bq m^{-3})				
Tour Code	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
CHI DONNA	29	86	25	9	37
CHI MAINTENANCE	408	685	862	287	561
CHI ROYAL	146	432	283	258	280
CHI TREZKIN	25	58	96	29	52
ROC ADVENTURE	21	34	51	28	33
ROC CAMMOO	52	112	185	36	96
ROC DEEPVAULT	21	46	56	35	39
ROC JOHANSENS	76	209	160	207	163
ROC OLSENS	16	33	34	25	27

TABLE 5. Seasonal and 12-monthly average [^{222}Rn] for caves tours in Group3.

		^{222}Rn Level (Bq m^{-3})			
Tour Code	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
ABE ARCH	22	31	11	141	51
ABE BUSHRANGERS	66	75	147	132	105
ABE GROVE	104	72	40	159	94
ABE KINGSOLOMONSTEMPLE	25	30	15	123	48
JEN BAAL	2789	3260	1859	629	2134
JEN CEREBUS	830	697	1073	481	770
JEN CHIFLEY	176	510	2011	656	838
JEN EXTBAAL	2140	2579	1774	582	1769
JEN EXTORIENT	318	1125	1495	480	854
JEN IMPERIAL	397	719	1193	967	819
JEN JERSEY		74	283	707	283 337
JEN JUBILEE	736	919	1996	1475	1282
JEN LUCAS	310	485	1433	287	628
JEN ORIENT	359	1321	1487	493	915
JEN RIBBON	331	1201	1845	676	1013
JEN RIVER	321	813	1920	509	891
WEE CAREYS	236	465	789	157	412
WEL CATHEDRAL	124	431	436		330
WEL GADEN	94	201	532		276
WOM FIGTREE	61	129	43	156	97
WOM JUNCTION	92	266	433	121	228
WOM KOORINGA	140	609	463	271	371
WOM MULWAREE	304	566	44	160	268
WOM WOLLONDILLY	169	437	141	133	220
YAR CASTLE	265	1163	3372	381	1295
YAR HARRYWOOD	441	338	295	273	337
YAR JERSEY	1277	1060	647	686	917
YAR JILLABANEAN	984	607	1268	436	824
YAR NORTHGLORY	549	1044	2946	314	1213

TABLE 6. Seasonal and 12-monthly average [^{222}Rn] for cave tours in Group 4.

		^{222}Rn Level (Bq m^{-3})			
Tour Code	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
BUC FAIRY	2089	3138	3369	1687	2571
BUC ROYAL	1248	1808	2818	984	1714
GUN GUNNSPLAINS	183	1147	4045	662	1509
HAS NEWDEGATE	619	1272	3171	1475	1634
MOL KINGSOLOMON	2891	2617	1712	2313	2383
MOL MARAKOOPA	210	325	974	278	447
MUR SHADESOFDEATH	1342	1680	1622	1112	1439

TABLE 7. Seasonal and 12-monthly average [^{222}Rn] for cave tours in Group 5.

	^{222}Rn Level (Bq m^{-3})				
Tour Code	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
KAT CUTTACUTTA	(1)	(1)	(1)	248	248
KAT TINDALL	(1)	(1)	(1)	89	89
KEL K9	292	378	216	629	379
KEL KELLYHILL	365	431	305	738	460
KEL MNTTAYLOR	537	573	115	1138	591
NAR ALEXANDRA	476	393	408	553	457
NAR BLANCHE	21	38	32	28	30
NAR VICFOSSIL	428	632	452	550	516
NAR WET	20	28	45	128	56
NEL PRNCSMARGROS	737	1029	2499	992	1314
TAN TANTANOOLA	242	292	254	294	271

Note (1) : No measurement (the commencement of monitoring at Cutta Cutta was delayed).

TABLE 8. Seasonal and 12-monthly average [^{222}Rn] forcave tours in Group 6.

	^{222}Rn Level (Bq m^{-3})				
Tour Code	**Winter**	**Spring$^{(2)}$**	**Summer**	**Autumn**	**Annual**
MAR JEWEL	851	960	(1)	409	740
MAR LAKECAVE	67	621	(1)	421	369
MAR MAMMOTH	28	47	(1)	130	68
MAR MOON	446	807	(1)	357	537
MAR YALLINGUP	729	770	701	664	716
YAN CABERET	41	89	49	122	75
YAN CRYSTAL	44	64	123	114	86

Note (1) : No measurement.
Note (2) : the Spring monitors at Margaret River were exposed for 7 months not 3 months. Corrections were made for the exposure time.

TABLE 9. Seasonal and 12-monthly average ^{222}Rn concentrations, for office locations and for cave maintainance

	^{222}Rn Level (Bq m^{-3})				
Group	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**
ABE MAINTENANCE (1)	52	56	83	134	81
BUC MAINTENANCE (1)	1474	2256	3369	1235	2083
GUN OFFICE	38	105		57	67
JEN MAINTENANCE (1)	55	213	613	87	242
WOM OFFICE	39	22	10	36	27

Note (1) : Radon levels derived assuming equal weighting at all measurement sites.

Tour Guide Radiation Dose

The tour guide radiation doses were calculated for those caves where work time data was available; no data was provided for Wellington, Yarrangobilly, Gunns Plains and the caves in Rockhampton. The assessed values for effective dose per year to each tour guide from inhalation of radon progeny are summarised in Table 10, grouped by geographical location. The distribution of these radiation doses is shown in Figure 2. Of the 116 tour guides for whom radiation doses could be assessed, 82 received doses less than 1 mSv per year. For comparison, the yearly average radiation dose to members of the public from natural radiation is about 1 - 2 mSv. Of the 34 tour guides receiving more than 1 mSv per year, only 4 were in excess of 5 mSv per year. The highest calculated dose was 9 mSv per year, less than one half of the current regulatory limit for occupational exposure to radiation.

Figure 2. Frequency distribution of annual radiation doses received by tour guides in Australian show caves, as determined from radon measurement data in this Survey.

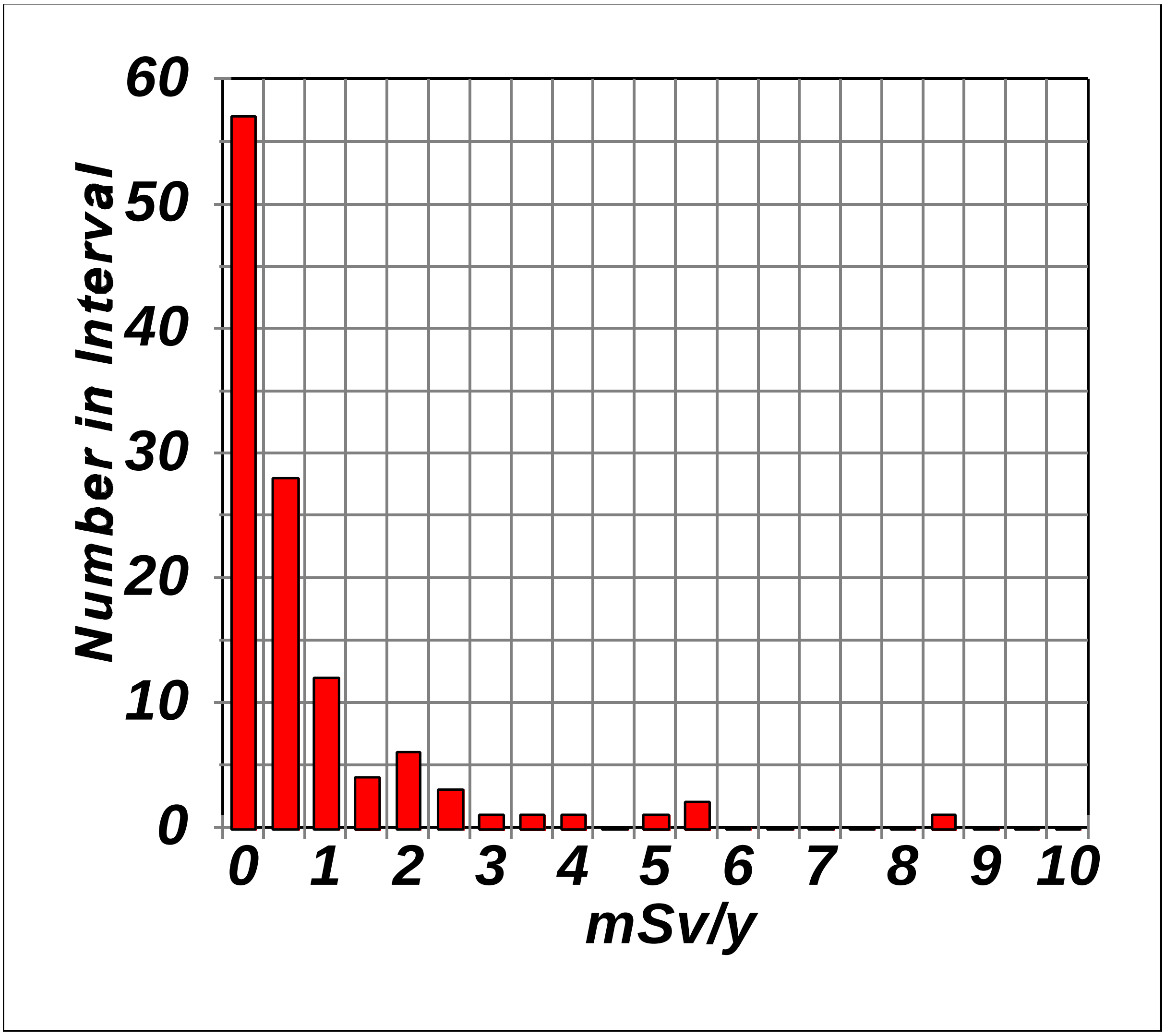

Table 10. Radiation dose (mSv) per year per tour guide from exposure to radon progeny, grouped by geographical location .

Annual Effective Dose (mSv/y)											
GROUP 1		**GROUP 2**		**GROUP 3**		**GROUP 4**		**GROUP 5**		**GROUP 6**	
UND 1	0.10	CHI 1	0.85	ABE 1	0.06	BUC 1	5.7	KEL 1	0.74	MAR 1	0.86
UND 2	0.08	CHI 2	1.0	ABE 2	0.06	BUC 2	8.9	KEL 2	0.31	MAR 2	0.65
UND 3	0.43	CHI 3	0.75	ABE 3	0.05	BUC 3	5.6	KEL 3	1.1	MAR 3	0.69
UND 4	0.43	CHI 4	0.60	ABE 4	<0.01	BUC 4	5.1	KEL 4	1.0	MAR 4	0.53
UND 5	0.43	CHI 5	0.17	JEN 1	0.19	HAS 1	2.7	KEL 5	1.1	MAR 5	0.53
UND 6	0.43	CHI 6	0.07	JEN 2	1.02	HAS 2	2.5	KEL 6	0.81	MAR 6	0.78
				JEN 3	0.59	HAS 3	1.3	KEL 7	0.11	MAR 7	0.32
				JEN 4	1.5	HAS 4	2.2	KEL 8	0.15	MAR 8	0.63
				JEN 5	1.9	HAS 5	2.0	KEL 9	1.2	MAR 9	0.30
				JEN 6	0.53	HAS 6	1.2	NAR 1	0.05	MAR 10	0.24
				JEN 7	3.4	HAS 7	0.96	NAR 2	0.52	MAR 11	0.16
				JEN 8	0.50	MOL 1	0.24	NAR 3	0.37	YAL 1	1.2
				JEN 9	0.47	MOL 2	4.3	NAR 4	0.02	YAL 2	1.07
				JEN 10	2.0	MOL 3	3.9	NAR 5	0.15	YAL 3	0.83
				JEN 11	2.4	MOL 4	0.89	NAR 6	0.19	YAL 4	1.2
				JEN 12	2.6	MOL 5	0.60	NAR 7	0.17	YAL 5	0.84
				JEN 13	1.1	MOL 6	0.87	NAR 8	0.31	YAL 6	0.33
				JEN 14	1.7	MOL 7	0.64	NAR 9	0.33	YAL 7	0.38
				JEN 15	2.5	MOL 8	0.58	NAR 10	0.16	YAN 1	0.16
				WEE 1	0.80	MOL 9	0.74	NAR 11	0.02	YAN 2	0.04
				WOM 1	0.24	MOL 10	0.23	NEL 1	2.1	YAN 3	0.04
				WOM 2	0.13	MUR 1	0.49	NEL 2	2.1	YAN 4	0.04
				WOM 3	0.06	MUR 2	0.25	NEL 3	1.2	YAN 5	<0.01
				WOM 4	0.16	MUR 3	0.12	NEL 4	0.75		
				WOM 5	0.26			TAN 1	0.31		
				WOM 6	0.03			TAN 2	0.31		
				WOM 7	0.04			TAN 3	0.34		
				WOM 8	0.03			TAN 4	1.35		
				WOM 9	<0.01						

DISCUSSION

There are a number of points to be made concerning the results in this study:

- the radiation track densities on many of the 12-month radon monitors in this study were very high, in many cases requiring an extrapolation beyond the calibrated range of the monitors. The 12-monthly and seasonal monitor results have been reported in *Appendix VI*. These results show that, in many cases, the radon levels from the 12-month monitors were about 50% higher than the summed results from the four seasonal monitors, while in a small number of cases this difference was up to a factor of two. The reason for this discrepancy is not understood and further studies are required to investigate the long-term behavior of the monitors in cave conditions. For this reason the annual radon concentrations were not determined from the 12-month monitor results but from the summed results of the four seasonal monitors.

- there are a number of gaps in the radon measurements for some locations:
  - due to delays in placing monitors at Cutta Cutta only Autumn exposures were obtained;
  - the commencement of monitoring at Kelly Hill was delayed by one season;
  - the Spring monitors at Margaret River were exposed for 7 months not 3 months. Corrections were made for the exposure time.

- The results for the first two seasons of the study show a marked variability in ^{222}Rn levels at some sites, up to a factor of two. Further, most show caves are visited during the day time; the values in this study reflect 24 hour averages. In previous studies in two of the caves in Group 4 (Solomon, 1992), a change in the ventilation during the day-time with increased human activity, was observed. For these caves it is possible that the 24 hour averages will over-estimate the day-time ^{222}Rn levels, but this observation cannot be generally applied to all the cave systems in this study.

- There are three main sources of measurement uncertainty in the assessment of the radiation doses. The radon monitor results in this study have an estimated measurement uncertainty of ±20%. The estimate of the equilibrium factor carries an uncertainty of ± 50%. The third uncertainty is in the use of the *conversion convention* for assessing effective dose from radon progeny exposure. While there is little data on the aerosol size or the radon progeny unattached fractions for Australian caves, earlier measurements at the Buchan caves using a wire-screen diffusion battery produced radon progeny particle size distributions with typical activity median diameter values of 1.1 nm and 170 nm for the upper and lower modes, respectively (Solomon, 1992). The average unattached fraction was 13.8%, indicative of the low particle concentration in caves, but higher than the value assumed to apply for application of the ICRP *conversion convention*. If these aerosol values are representative of Australian caves, then applying the ICRP Respiratory Tract Model (ICRP 66, 1994b) leads to values for the effective dose that are up to a factor of two greater than the doses derived using the ICRP dose *conversion convention*.

Subject to these qualifications, the preliminary estimates of radiation dose from this study would suggest that all tour guides within Australia receive less than the occupational limit of 20 mSv per year, while most receive less than 5 mSv. The work practices and time spent in the caves by electricians and maintenance workers needs to be studied in more detail.

RECOMMENDATIONS

The regulation of occupational exposure to radiation is the responsibility of the appropriate State authority. There are State regulations covering workplace exposure to radiation during the mining and milling of radioactive ores. There are presently no regulations covering workplace exposure to natural radiation. The Australian National Health and Medical Research Council (NH&MRC) and the National Occupational Health and Safety Commission (NOH&SC) have prepared jointly recommendations and standards based on the ICRP 65 recommendations (ICRP, 1994a), for application in the Australian context (NH&MRC, 1995; NOHCS, 1995). In particular, these documents propose an *action level* for ^{222}Rn in the workplace of 1000 Bq m^{-3}. For workplaces with radon levels in excess of this *action level*, the preferred option is to modify the workplace conditions in order to reduce the radon levels to below 1000 Bq m^{-3}. If this reduction is not possible, then it may be necessary to implement radiation monitoring programmes to ensure compliance with regulatory radiation limits. In practice, this would mean that some tour guides working in locations with conditions exceeding the *action level* would be treated as "radiation workers" and individual radiation records would need to be maintained to ensure that no tour guide receives more than 20 mSv per year.

For the present study, the relevant number for comparison with the *action level* is *the yearly average radon level for a complete cave tour*. On this basis, only a small number of cave tours (of the order of 20%) were found to exceed the *action level*. Some caves had radon levels exceeding 1000 Bq m^{-3} at some locations or for one or two seasons of the year, but the the yearly average radon levels for tours of these caves were below the *action level*.

The results of the present survey can be divided into three categories when considering methods for limiting occupational exposure to radon.

- **Cave where all tours fall below the radon action level**

  This category covers the majority of show caves in Australia, and includes caves located at: Undara Lava Tubes, Chillagoe, Rockhampton, Abercombie, Wee Jasper, Wellington, Wombeyan, Cutta Cutta, Kelly Hill, Naracoorte, Tantanoola, Margaret River, Yallingup and Yanchep.

  For cave tours in these locations it should not be necessary to implement any measures to control radon or to monitor individual tour guide exposure. Radon is present in most of these caves in varying amounts and for those locations close to the *action level* it may be prudent to remeasure radon levels at a later time if there are any changes to the conditions within the particular cave.

- **Caves where some tours exceed the radon action level**

  Locations in this category include: Jenolan, Yarrangobilly and Mole Creek.

  The caves at Yarrangobilly and Mole Creek have a low rate of tourist visits, but the caves at Jenolan have the largest number of tourist visits of any cave in Australia. Control of exposure in these locations depends on the ability of the cave management to limit the access to those tours with radon levels exceeding the *action level*. There is marked seasonal variability in radon levels for many of the caves, and it may be possible to restrict access to some cave locations at particular times of the year in order to ensure that the tour guides work under conditions with radon below the *action level*. This type of cave management would require more information on the behaviour of radon and radon progeny in the affected caves; the current estimates of radon are based on 24 hour averages and may not accurately reflect the radon levels during the day-time work period. They also only cover a single year of measurements. Future studies should cover diurnal radon variation, atmospheric pressure effects, radon equilibrium factors and aerosol conditions for caves exceeding the *action level*. Some studies on radon progeny levels and interim personal monitoring of tour guides are already in progress at Jenolan, but further long-term studies are needed. If access cannot be controlled then it would be necessary to designate the guides in such areas as radiation workers and to maintain detailed radiation exposure records in order to demonstrate compliance with future regulatory radiation dose limits.

- **Caves where all tours exceed the radon action level**

All caves in this category are within Victoria and Tasmania: Buchan, Murrindal, Nelson, Gunns Plains and Hastings.

It is normally expected in workplaces with radon levels above 1000 Bq m^{-3} that active measures be taken to reduce the radon concentration, usually by improving the ventilation. Increasing the ventilation in show caves is not possible since it affects the delicate balance of carbon dioxide, partial pressure, temperature and humidity, with the risk of damage to cave decoration. The alternative is to designate the workers in such areas as radiation workers and to maintain detailed radiation exposure records in order to demonstrate compliance with regulatory radiation dose limit. However, the caves in this category other than Buchan have low visitation rates, leading to annual radiation doses of the order 2 mSv or less. The implementation of an intensive radon monitoring programme may not be justified for these caves. The caves at Buchan have a large number of tour visits and high radon levels. This is reflected in the magnitude of the radiation dose estimates. The policy of the cave management to restrict individual hours spent in the Buchan caves to less than 1000 hours per year has constrained the radiation doses to less than 10 mSv per year. For the caves at Buchan it is likely that some form of radiation monitoring, either personal or area, will be required. Before such monitoring programmes are contemplated it is recommended that the radon and radon progeny levels be studied in more detail, in particular the diurnal behaviour of radon and the long-term values for the radon equilibrium factors and the aerosol conditions, in order to improve the radiation dose estimates.

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AN AUSTRALIA-WIDE STUDY OF RADON LEVELS

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Radon is a naturally occuring radioactive gas. It comes from the radioactive decay of uranium, which is present in small amounts almost everywhere in the Earth's crust. When a radioactive atom decays, its nucleus, which is unstable, breaks down, turning into the nucleus of another element, called progeny. At the same time, a small burst of radiation is released in the form of an alpha particle or a beta particle or one or more gamma rays. Uranium breaks down through a series of radioactive progeny, which usually remain chemically attached to the material containing the uranium, until radon is formed. Radon, being chemically inert and a gas, does not combine with the atoms of its host material; instead it works its way through the tiny cracks and voids in the ground and into the atmosphere, where it can be inhaled in the air we breathe. Radon is thus a natural fact of life.

How does radon affect health?

The radon gas in turn produces radon progeny which are also radioactive. When we breathe in radon and its progeny, some radioactive decays take place inside our lungs. The alpha particles produced can cause damage to lung tissue. Such damage can lead to lung cancer. There is a delay of many years between the initiation of a cancer by radiation and its growth to a size which can be observed clinically. The risk of developing lung cancer from exposure to radon depends on how much radon progeny we breathe in. The more radon progeny there are in the air, the bigger the risk. Similarly, the longer we spend breathing in the radon progeny, the greater the risk.

How is radon measured?

The quantity of radon present in the air can be measured by using sensitive equipment to detect and count the radiations emitted when atoms of radon and its progeny decay. Because radon concentrations in the environment are low and variable, radon measurements are usually made using a monitor that accumulates information over a long period, typically 3 months to 1 year. The measurement is made in terms of **activity**, which is the number of radioactive decays of radon atoms per unit time, and which is proportional to the number of radon atoms present. Activity is measured in units called **becquerels**. If the air contains one becquerel of radon per cubic metre (1 Bq m^{-3}), it means that, on average, there will be one radioactive decay of a radon atom per second for every cubic metre of air.

Where is radon a problem?

In outdoor air, radon concentrations are low. If we collected one hundred million, million, million molecules of air (about a teaspoonful) we might expect to find about ten radon atoms amongst them. Indoors or underground, however, the concentration of radon can be higher, as confined spaces have the effect of trapping radon for a while. Radon levels are typically very variable, depending on the flow of air through the location. There are places where radon levels can be very high: in some caves, for example, or in a poorly ventilated underground uranium mine.

How serious are the health risks?

The assessment of health risk is based largely on evidence of the incidence of lung cancer among uranium miners in the past. Modern mines are well ventilated to keep radon concentrations low but, in earlier times, uranium miners received quite high radiation doses from the radon progeny they inhaled. On the basis of available evidence, risk estimates have been made relating the risk of developing lung cancer to the concentration of radon in air. Because the problem is a very difficult one to study, there are several different estimates by different scientific research teams, but the risks are generally consistent with a range of about one to two fatalities in a million per Bq m^{-3}. This means that if one million people were exposed for a year to radon in air at a concentration of 1 Bq m^{-3} in the environment, one or two of them might be expected to die, eventually, from radiation-induced lung cancer.

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