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RADON IN THE WORKPLACE—A STUDY OF OCCUPATIONAL EXPOSURE IN BT UNDERGROUND STRUCTURES

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Abstract—During the period August 1993–October 1994 a study was undertaken throughout British Telecommunications plc to assess occupational exposure to radon. This paper is concerned only with that portion of the work concerned with underground structures. The results show that radon can build up to very high concentrations in manholes and implies a significant risk to those who need to work in them. For various reasons, which are explained, exposures are much less than predicted and in all but a very few cases the annual predicted radiation dose due to radon is expected to be below 5 milliSieverts (mSv). A safe system of work is described which seeks to ensure that no BT people receive an annual radiation dose of greater than 5 mSv as a result of occupational exposure to radon. Copyright © 1996 British Occupational Hygiene Society.

INTRODUCTION

Occurrence and health risks

Radon-222 is a naturally occurring radioactive gas formed from the decay of uranium which is present in small amounts in certain types of rock. Once produced it can permeate the surrounding rock and soil and rise to the surface. In open areas it is quickly diluted to insignificant levels. However, if trapped in underground structures it can accumulate to much higher levels.

The principal health risk is associated with radon *daughters* or radon *progeny*, formed from the radioactive decay of radon. Unlike radon these are particulate in nature and, once inhaled, can become trapped in the lungs. Once there they can continue to irradiate the lung, even after initial exposure has ceased, thus increasing the risk of lung cancer. This risk increases with the duration of initial exposure and the concentration of radon daughters present.

Advice and regulation concerning radon

The National Radiological Protection Board (NRPB) have, as part of their advice concerning radon, defined radon affected areas (NRPB, 1990, 1992, 1993a,b) as those in which 1% of homes in that area would be expected to exceed a radon gas concentration of 200 Becquerels per cubic metre (Bq m^{-3}).

At the time of writing the whole of the counties of Cornwall, Devon and Northamptonshire have been declared affected areas, as well as parts of Somerset, Derbyshire, Scotland and Northern Ireland.

The Health and Safety Executive (HSE) have also given advice concerning radon in the workplace. In addition to the statutory duties imposed on employers under the

Ionising Radiations Regulations 1985 (IRR) and associated Approved Code of Practice (ACOP), they have defined a workplace Action Level (HSE, 1992) of 400 Bq m^{-3} which is comparable to the NRPB Action Level of 200 Bq m^{-3} set for homes.

Thus, unless employers can show that radon concentrations are less than 400 Bq m^{-3}, action will be required to comply with the IRR 85.

The BT underground network

The BT telecommunications network divides the country into numerous telephone areas, each being served by a telephone exchange (TE). From the TE, underground cables are sent out initially to distribution points called *Cabinets Cross-connection* (the dark green boxes often seen on pavements), and then on to the customer via further underground or overground cables. In addition TEs are linked together through trunk cables which permit calls in one telephone area to be directed to a recipient in another.

Throughout the underground network various access points have been provided. These range in size and structure from shallow carriageway boxes which are typically no more than 1 m deep, with an internal volume of generally less than 2 m^3, to deep shafts and tunnels which can be up to 20 m deep with large internal volumes. There are, however, very few of these deeper structures. Manholes form a substantial proportion of all access points. They are typically around 3 m deep with an internal volume in the range 4–20 m^3. The underground cables pass through the manhole and thus permit access to telephone engineers for maintenance and repair.

The cable ducts which hold the cables are generally unsealed and this allows gases and water to collect and flow between them. It has been estimated that BT has approximately 10 000 manholes in the affected areas and a population of hundreds of telephone engineers who are potentially exposed to radon.

STUDY PROTOCOL

In August 1993 a comprehensive study of radon in underground workplaces commenced. The study focused on three key areas of assessments.

- —Static measurements: to assess the extent of the hazard by measuring the average concentration of radon in manholes.
- —Personal dosimetry: to assess the degree of risk presented to BT engineers who work in manholes.
- —Kinetic measurements: to determine the rate of radon dissipation under various ventilation regimes. These data were used to validate control strategies.

These three study objectives will be discussed in greater detail.

Static measurements

Manholes have been constructed from many different materials including brick, concrete and steel-reinforced concrete. Several shape variations exist ranging from rectangular structures with a central vertical access shaft to coffin-shaped turning manholes with an offset vertical access shaft (see Fig. 3).

The selection procedure ensured that the entire affected area was considered and that a representative sample of the various structural types was obtained. Carriageway boxes were not included in the static measurement study. This was because none is greater than about 1 m deep and previous measurements had shown that any radon present rapidly dissipates on opening.

The measurements were made using passive track-etch detectors (Miles and Dew, 1990; Wrixon *et al.*, 1988; Gilrin and Bartlett, 1988) over a period of approximately 90 consecutive days. Detectors were supplied in radon-proof bags which were riveted onto an inside wall of the manhole.

At the beginning of the sampling period a slit was cut into the bag to allow the manhole air to diffuse into the detector. Each detector was positioned as low as possible in the manhole, but above the indicated water level in manholes prone to flooding.

Signs were placed in each manhole advising that a radon measurement was in progress and the number of times each manhole was accessed during the period of measurement was recorded.

At the end of the measurement period the detectors were analysed according to the approved method (NRPB, 1991) and the average radon concentration in Bq m^{-3} was determined. Correction factors (Dixon, personal communication) were applied to the raw data to take account of seasonal variations in radon concentration.

Personal dosimetry

In addition to the static radon measurements an assessment of personal exposure was undertaken. In each affected area, volunteers for the study were invited from the population of engineers who regularly work in underground structures.

Each wore a personal track-etch detector pinned to his lapel for a period of approximately 30 consecutive days. An activity log was kept during the measurement period to record the time spent working in underground structures.

The original results derived from this part of the study showed a number of anomalies. For this reason it was decided to repeat the measurements using a modified study protocol. These two components of the personal dose assessment have retrospectively been termed Phase I and Phase II.

Phase I dosimetry. Ten volunteers from each affected area were included, each of which worked regularly in manholes. Their activity log recorded the location worked, the time the monitor was put on and taken off each day, and the number of hours worked in manholes.

At the end of the measurement period their radiation dose was determined and recorded in mSv. A predicted annual dose was calculated from the 30 day figure by linear extrapolation and took into account the nominal hours worked per year.

Phase II dosimetry. Twenty-five volunteers from each affected area were included in the Phase II study. Twenty of these constituted the sample group who regularly worked in underground structures as part of their normal duties. The remaining five constituted the control group who were based in an affected area but never worked in underground structures.

The activity log from Phase I was revised to include details of both the time spent in, and the number of visits made to, various underground structures. Since the detectors were stored in the engineer's vehicles when not being worn a detector was placed in each vehicle to determine whether there was any contribution to total dose during storage.

Shortly after the end of the Phase I study the NRPB published details of two new affected areas in Scotland. These were included in the Phase II study. Again the measurements were made over a period of approximately 30 consecutive days.

Kinetic measurements

The two main study areas focused on the dispersion rates of nitrous oxide and radon daughters from underground structures and the estimation of the equilibrium factor between radon and radon progeny. The protocol in each case will be described.

Nitrous oxide dispersion measurements. The objective of this part of the study was to use nitrous oxide as a surrogate for radon to characterise the rate of dispersion under natural and assisted ventilation conditions in various manholes.

Assisted ventilation was achieved by suspending a plastic sheet halfway across the entrance shaft to the manhole so that it projected about 0.75 m out from the manhole and extended to 0.5 m from the manhole floor. This configuration encouraged air to flow through the manhole.

The procedure involved introducing a known volume of nitrous oxide into each manhole which was mixed to constant concentration with a high volume pump. The manhole lid was then lifted and the decay of concentration measured using a MIRAN 1A infra-red gas analyser (see Fig. 1).

Radon daughters dispersion measurements. A Thompson and Neilson Instant Radon Progeny Meter (IRPM) was used to measure the dispersion of radon progeny from the various manhole types throughout Devon and Cornwall. The procedure involved lifting the lid of the manhole and immediately replacing it with a purpose built Perspex lid. This permitted the initial radon daughter concentration to be measured. The Perspex lid was then removed and the IRPM lowered into the manhole to just above water level. Further readings were taken every 5 min under various ventilation regimes until the radon daughter concentration had dropped to approximately 40 Bq m^{-3} or below. The equipment configuration used for these measurements is shown in Fig. 2.

Equilibrium factor estimation. The equilibrium factor, *F*, expresses the ratio of the total potential alpha energy of the actual decay product concentration to the total potential alpha energy that the decay products would have if they were in equilibrium with the radon. The workplace Action Level of 400 Bq m^{-3} assumes an equilibrium factor of 0.5, however, it has been shown that in underground structures, such as mines, the equilibrium factor can be higher. Thus in order to validate the personal and static measurements it was necessary to show that the equilibrium factor in manholes was approximately 0.5. A simple procedure for estimating the value of *F* involves the simultaneous measurement of radon and radon progeny. The IRPM was used to determine the concentration of radon progeny and a Lucas Cell (Bowring, 1992) to determine radon (see Fig. 2). The air entering the cell was filtered to remove the radon daughters.

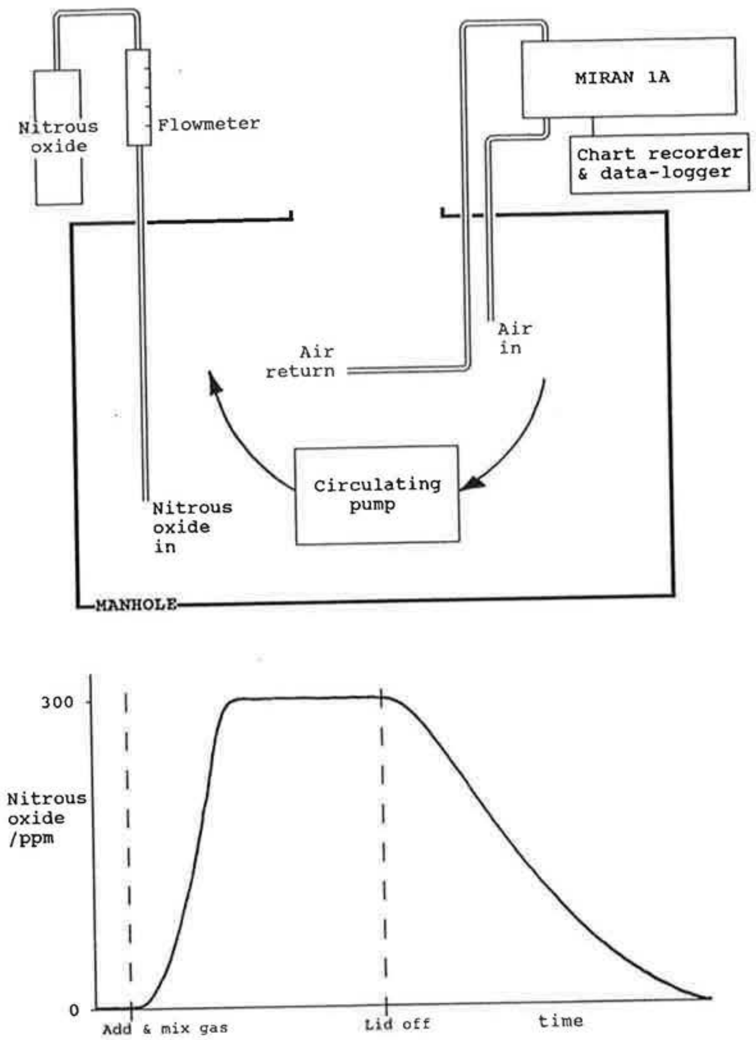

Fig. 1. Equipment configuration—nitrous oxide dispersion kinetics.

RESULTS

Static measurements

Seasonally corrected radon concentration data are presented by the radon affected areas in Table 1.

Personal dosimetry

As explained in the previous section on 'Study Protocol' two separate personal monitoring exercises were undertaken; Phase I and Phase II. The results are presented for each affected area in Tables 2 and 3.

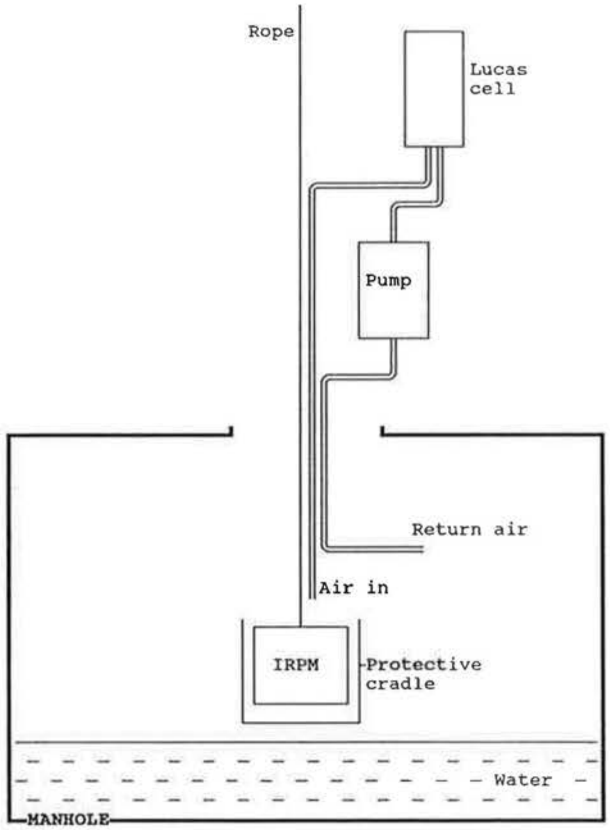

Fig. 2. Simultaneous measurement of radon and radon progeny.

The actual 30-day radiation dose and the predicted annual dose obtained by extrapolation of the 30-day data are recorded.

The average corrected radon concentration recorded by the vehicle monitors (see sub-section on 'Phase II dosimetry') was 13 Bq m^{-3}. This was insufficiently large to influence the personal dosimetry data.

Dispersion measurements

Nitrous oxide dispersion measurements. Table 4 summarises the data obtained from this part of the study. The data represent the time taken for the nitrous oxide concentration to fall to approximately one-tenth of its original concentration.

Figure 4 shows the ventilation data graphically for manhole type MRT8.

Radon daughter dispersion measurements. The radon daughter (RD) dissipation data obtained from studies in Cornwall and Devon are summarised in Tables 5 and 6.

The initial and final RD concentrations measured in each manhole are shown, along with the total time elapsed between initial and final concentrations (t_{TOT}). To enable a comparison to be made of the different reduction times under the two forms

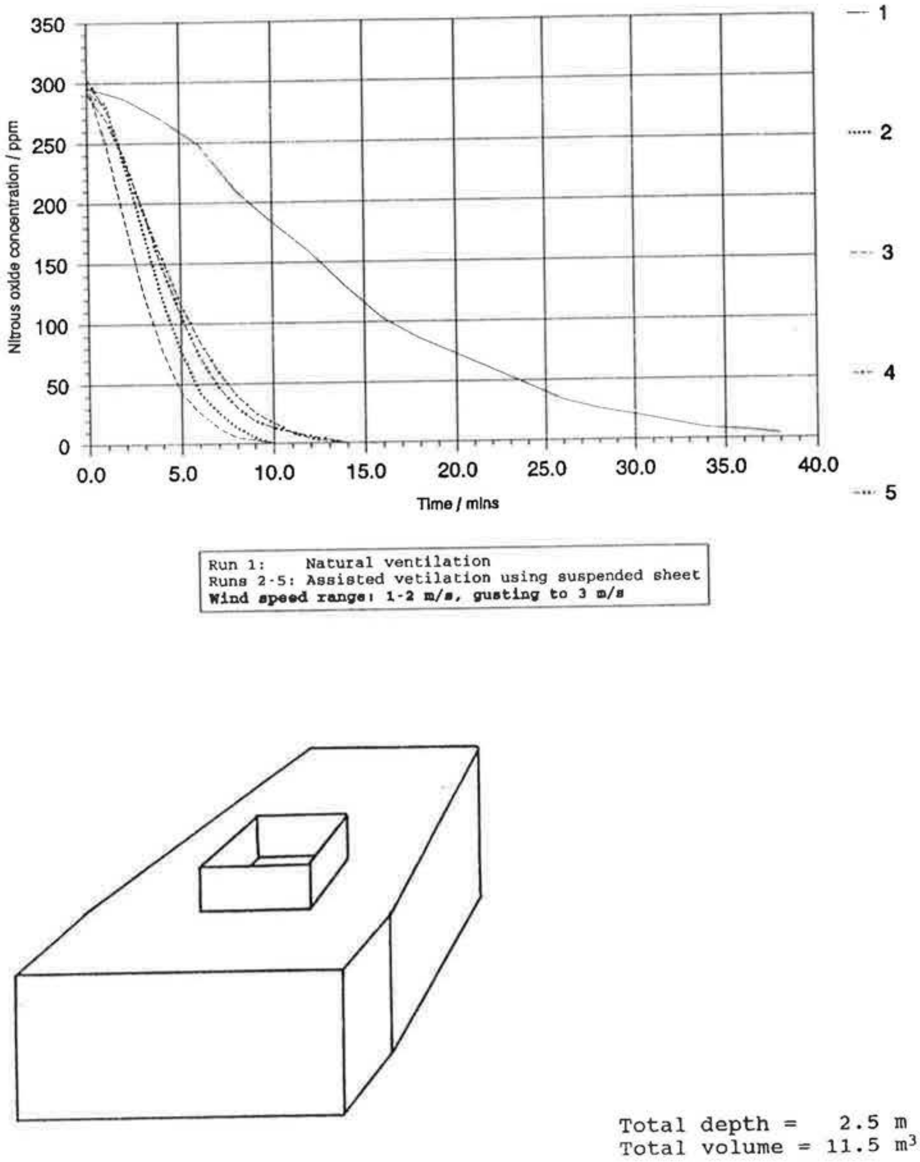

Fig. 3. Manhole gas dispersion kinetics using nitrous oxide tracer. Manhole type: MRT8.

of ventilation, the time taken for the concentration to fall to one-tenth of its initial level is also shown ($t_{0.1}$).

Equilibrium factor estimation. Data obtained from the simultaneous measurement of radon and radon daughters are presented in Table 7. The equilibrium factor has been estimated in each case.

Table 1. Phase I static measurement results

Radon affected area	No. of results	Mean radon concentration (Bq m^{-3})	Minimum radon concentration (Bq m^{-3})	Maximum radon concentration (Bq m^{-3})
Cornwall	18	2508	53	13 639
Devon	21	1667	53	8097
Somerset	20	1564	70	3975
Derbyshire	20	1933	9	11 245
Northamptonshire	20	1200	65	4629
Scotland—Grampian	20	755	34	2487
Scotland—Highland	20	2092	14	10 570
N. Ireland	19	1028	64	6707

All areas: mean = 1416 Bq m^{-3}; min = 9 Bq m^{-3}; max = 13 639 Bq m^{-3}.

Table 2. Phase I dosimetry results

Affected area	*n*	Dose range (mSv)	Predicted annual dose range (mSv)
Cornwall	10	0.1–0.6	1.1–6.7
Derbyshire	10	<0.1–0.9	<1.1–10.1
Devon	10	<0.1–0.3	<1.1–3.4
Northamptonshire	8	<0.1–0.5	<1.1–5.6
Somerset	9	<0.1–0.6	<1.1–6.7

Table 3. Phase II dosimetry results

Affected area	Group	*n*	Dose range (mSv)	Predicted annual dose range (mSv)
Cornwall	Sample	17	<0.1–0.4	<1.1–4.5
	Control	5	0.2–0.4	2.2–4.5
Devon	Sample	17	<0.1–0.3	<1.1–3.4
	Control	4	<0.1–0.1	0.7–1.1
Somerset	Sample	19	<0.1–0.3	<0.8–2.6
	Control	5	<0.1	<1.1
Derbyshire	Sample	16	<0.1–0.2	<1.1–2.2
	Control	4	<0.1–0.2	<0.8–2.0
Northamptonshire	Sample	13	<0.1–0.2	<0.8–2.5
	Control	4	<0.1	<1.1
Grampian	Sample	5	<0.1–0.7	<0.8–6.2
	Control	2	<0.1	<0.1
Highland	Sample	9	<0.1–0.8	<0.4–7.2
	Control	3	<0.1–0.3	<1.1–3.4

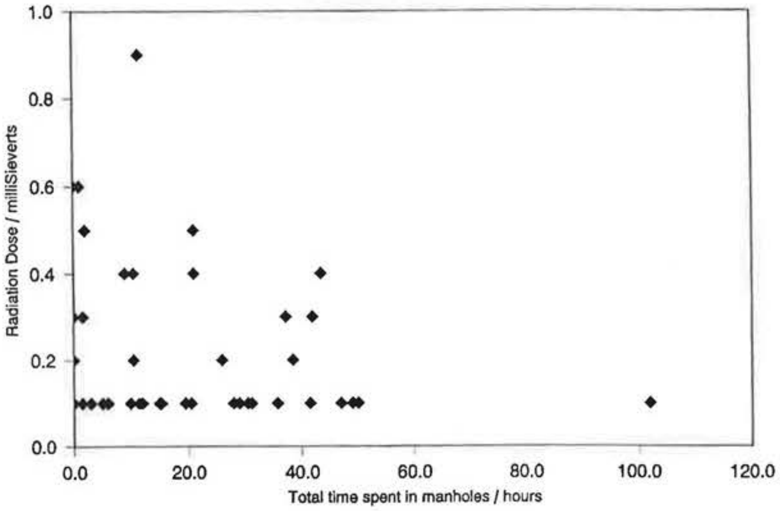

Fig. 4. Personal dosimetry—Phase 1. Thirty-day dosimetry data (all areas) vs time spent in manholes.

Table 4. Summary of data for nitrous oxide dispersion

Manhole type	Natural ventilation (min)	Assisted ventilation (min)
MR7	52	5
MRT8	28	6–9
MR4	10	5–7

Table 5. Natural ventilation

Manhole	Initial RD concentration (Bq m^{-3})	Final RD concentration (Bq m^{-3})	t_{TOT} (min)	$t_{0.1}$ (min)
1	4680	31	60	18
2	643	15	15	12
3	472	46	35	35
4	1034	207	60	>60
5	893	72	20	18

Table 6. Assisted ventilation

Manhole	Initial RD concentration (Bq m^{-3})	Final RD concentration (Bq m^{-3})	t_{TOT} (min)	$t_{0.1}$ (min)
6	240	12	15	10
7	153	15	20	15
8	434	18	20	15
9	1605	0	20	10
10	435	5	10	5
11	1636	55	30	10
12	128	0	10	5

Table 7. Equilibrium factor

Measurement	Radon concentration ($Bq\ m^{-3}$)	Radon daughter concentration ($Bq\ m^{-3}$)	Equilibrium factor
1	1082	472	0.44
2	4559	2135	0.47
3	145	66	0.46
4	2001	898	0.45
5	663	341	0.51
6	12 705	4680	0.37

Average equilibrium factor = 0.45.

DISCUSSION OF RESULTS

Static radon measurements

The static measurement of radon was intended to provide information on the degree of hazard from radon in manholes.

Guidance issued by the Health and Safety Executive equates the annual radiation dose of 5 mSv applicable to members of the public to a workplace radon concentration of 400 $Bq\ m^{-3}$. Above this level action must be taken to comply with the IRR 85. In particular all workplaces above 400 $Bq\ m^{-3}$ would need to be designated supervised areas and those above 1200 $Bq\ m^{-3}$ would constitute controlled areas (as defined in the regulations).

In workplaces other than buildings, however, the $Bq\ m^{-3}$ data presented in Table 1 cannot be compared directly with a radiation dose of 5 mSv per annum. This is because the adjustment that is applied for diurnal variations in radon level may not be appropriate for manholes, with the result that doses might be underestimated. In order to make an accurate comparison between radiation dose and radon concentration a specific criterion would need to be developed for a typical manhole environment. In the absence of such a criterion a conservative estimate may be obtained using the analogy of a mine. In such environments 220 $Bq\ m^{-3}$ is usually taken to be equivalent to 0.03 working levels which is the concentration at which the IRR 85 require a supervised area to be designated.

It can be deduced from the static measurement data that over three-quarters of all manholes in affected areas are expected to exceed 220 $Bq\ m^{-3}$, many by a substantial margin. It is estimated that BT has some 10 000 manholes in the affected areas which implies that within this population there would be 7500 workplaces subject to the requirements of IRR 85.

The vast majority of manholes are in the public domain, being located along pavements and walkways or alongside roads. The designation of supervised and controlled areas and associated demarcation with warning signs bearing the radiation trefoil has the potential to generate public concern.

Because of the nature and construction of the underground network it was not feasible to provide permanent engineering controls or to seal manholes to prevent the ingress of radon. Thus the solution lay in the enforcement of a system of work which ensured that, at the time of entry, a controlled or supervised area did not exist.

Personal dosimetry

The aim of the personal dosimetry programme was to quantify the level of risk to BT people who work in manholes.

Because of the inherent uncertainty in the accuracy of the track-etch detector at low exposure levels much of the data presented in Tables 2 and 3 is too small to be analysed in absolute terms. Nevertheless, examination and comparison of the Phase I and Phase II data does reveal several anomalies which will be discussed.

(1) Static measurements concluded that many manholes had very high radon concentrations, in the order of thousands of Bq m^{-3}. The personal dosimetry data show, however, that doses are very much lower than would be expected from exposure at these radon levels. Apart from three volunteers in the Phase I study and two volunteers in the Phase II study, none are expected to exceed the 5 mSv per annum limit for members of the public. Of those with the potential to exceed 5 mSv per annum, the highest extrapolated dose was calculated to be 10.1 mSv.

It is worthy of note that the two volunteers from Scotland who recorded predicted annual doses greater than 5 mSv did not work in any underground structures within either affected area during the duration of the study. For this reason a further personal dosimetry study covering the whole of the KW postal district is currently in progress.

(2) No linear correlation was observed between the time spent in, or the number of visits to, manholes and radiation dose. Intuitively one would expect dose to increase in a roughly linear fashion with the number of hours worked in, or number of visits to, manholes. Yet in both the Phase I and Phase II study, no such relationship was observed. (Figures 4–6 show scattergrams of the dose data for both Phase I and Phase II. Linear regression coefficients were 0.17, 0.28 and 0.10, respectively.)

(3) There was no statistical difference observed in a two-sample *t*-test between the mean dose received by the sample and control groups from the Phase II study. Again

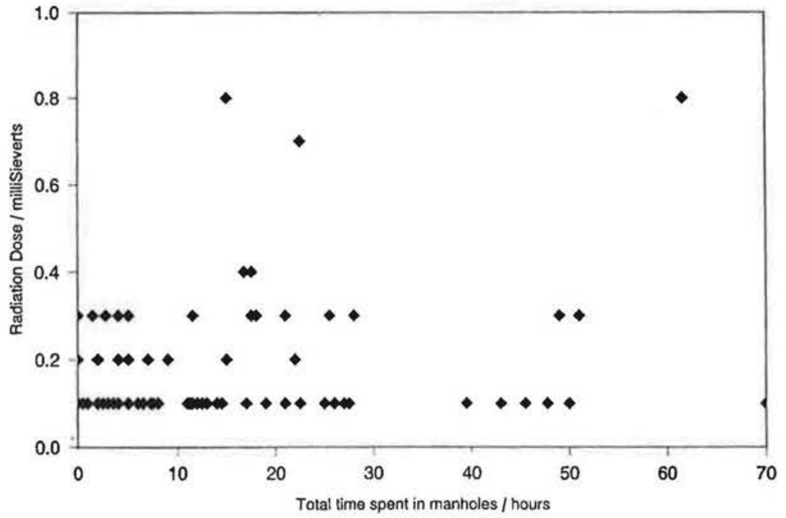

Fig. 5. Personal dosimetry—Phase 2. Thirty-day dosimetry data (all areas) vs time spent in manholes.

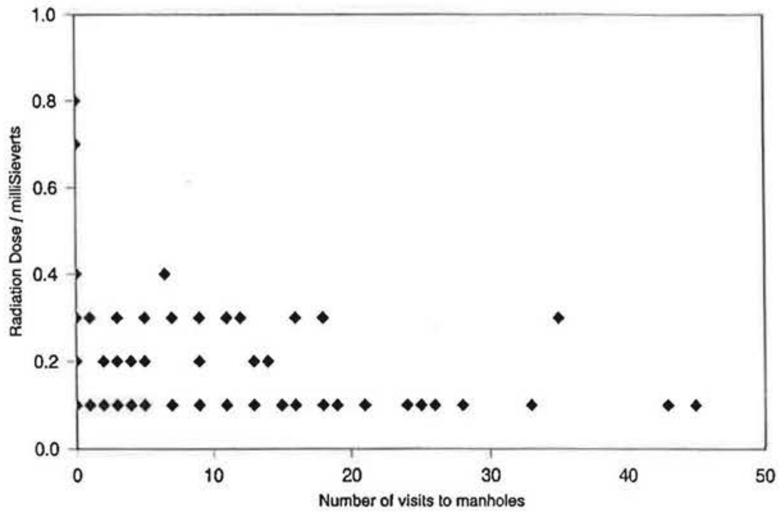

Fig. 6. Personal dosimetry—Phase 2. Thirty-day dosimetry data (all areas) vs number of visits to manholes.

the hypothesis is that work in manholes known to contain high concentrations of radon will increase radiation dose above the background dose expected for BT people working in an affected area. The data, however, did not support this hypothesis.

The best explanation for these observed anomalies comes in three parts. First, the entrance shaft and cable ducts of manholes are not sealed against the ingress of water. Thus it is observed that more than 90% of all manholes contain water up to half their depth, which needs to be removed before work can commence. This is achieved using a portable pump, and typically this process can take from 10 to 30 min to complete. During this time the concentration of any radon present in the manhole will be substantially reduced by displacement and dispersion.

Second, before the manhole can be entered two mandatory gas tests must be performed to check for the presence of flammable or asphyxiating atmospheres. These take a nominal 10 min to complete and thus provide a further time interval for radon dispersion.

Third, manholes have a relatively small internal volume usually in the range 4–20 m^3, but typically about 10 m^3. A substantial proportion of the air contained in a manhole will be displaced on entry, thus providing another mechanism for dilution of any radon present.

These three factors provide an explanation as to why the substantial hazard inferred by static measurement is not translated to a proportionately high level of risk for BT engineers working in manholes.

Nevertheless, there is still a residual risk principally associated with those 10% of manholes which do not contain water, and thus can be entered after completing the mandatory gas tests. In addition there is the small population of deeper structures where the impact of displacement and dispersion on the radon concentration is very much less than for manholes up to 3 m deep. Thus it is reasonable to propose that the few volunteers who did record predicted annual doses above 5 mSv received a significant proportion of that dose from work in such manholes.

To deal with this problem, a safe system of work was formulated which, in essence, deals with these two areas of concern.

The kinetic studies described in the sub-sections on 'Kinetic measurements' and 'Disperson measurements' validated the use of a suspended sheet for increasing the rate of radon dispersion from manholes up to about 3 m deep. This technique is now applied for 10 min in the 10% of manholes where water ingress is not a problem. This period coupled with the 10 min required for the gas tests is sufficient to reduce any radon present to below 400 Bq m^{-3}. The suspended sheet method, however, is only effective in manholes up to about 3 m deep. In the deeper structures an air blower is used which is capable of delivering 30 m^3 min^{-1} of fresh air. Application of the blower for 10 min prior to entry will reduce any radon present to below 400 Bq m^{-3}.

The safe system of work came into force in February 1995 and is being supported by a programme of personal dosimetry in all radon affected areas to confirm its effectiveness in the field.

No BT employees working in manholes should exceed a radiation dose of 5 mSv per annum as a consequence.

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