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The Observation and Analysis of Cancer Deaths among Classified Radiation Workers

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ABSTRACT. The extent to which occupational radiation exposure contributes to cancer mortality is an influence on future world energy policy. It is also a factor in deciding the level of expenditure to reduce radiation levels experienced by workers. Here we discuss some of the difficulties in analysing the situation and present the results of some calculations which estimate the expected age-specific radiation mortalities from all inducible cancers and also from leukaemia separately. Using a high value for the average occupational exposure and a conservative estimate of the associated risk, we find that a survey of mortality among radiation workers must run over many years before sufficient data would be accumulated to resolve the effects of radiation-induced neoplasms from those arising from other causes. We show the advisability of determining the cause of death both of persons who remain employed in the industry and all persons who enter and subsequently leave the industry, perhaps being employed in it for only a short time. Our estimates are based on maintenance of an occupationally exposed dose of one rad per person per year during the period of the survey which may extend over several decades. However, scaling of the estimates to any other exposure rates is easily performed.

We also give estimates of the lowest risk coefficients detectable in a given observation time. Since for a work force of 3000 these lowest detectable values are an order of magnitude larger than those expected, it is clear that only a national or international survey can produce data adequate for even modest objectives.

1. Introduction

The widespread use of radioactive isotopes, X-ray equipment, neutron generators and the rate of expansion of the nuclear power industry has raised questions about the carcinogenic effects of radiation at the levels experienced by operational workers. We are not concerned in this paper with exposure resulting from accidents, neither are we concerned with the mechanisms of carcinogenesis. Our prime objectives here are to assess the prospects of drawing any conclusions from a survey of causes of death of radiation workers; to identify the factors which influence these prospects; to estimate the effects of latency of radiation effects on the age-specific death rate; and to provide basic information from which the relative magnitude of radiation-induced and natural cancers can be estimated. All of these factors are relevant considerations in the setting up of a survey. The ultimate value of a survey will be determined by the information contained within the collected data. Before establishing the data base it is prudent to attempt to anticipate the demands which will be made on it. This paper reports such an attempt.

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In section 2 we describe the model we have used to represent a work force of radiation workers and the way in which we have estimated their chances of dying from an induced cancer. Section 3 discusses the time necessary to achieve sufficient data to be able to draw conclusions with some specified level of confidence. We also consider the magnitude of risk that is detectable in a given time.

Results of calculations are presented and discussed in section 4 and we make comments on possible conclusions in the final section.

2. The model

There are three aspects to be settled before any calculations can be carried out:

(i) the age distribution of the work force and the rate at which workers leave,
(ii) the natural incidence of deaths from causes which may also be induced by radiation, and
(iii) the risk of death due to exposure to radiation and how this risk is distributed in time.

2.1. *The work force*

Our calculations refer to a work force of 100 000 distributed in age as shown in fig. 1. This distribution is based on the actual distribution at an established nuclear energy site and does not differ greatly from any typical British industry. We have assumed for simplicity that the annual percentage leaving radiation work other than by death or retirement is the same for every age group. Stability of the distribution is maintained by introducing new workers (with no previous industrial radiation exposure) to replace those leaving any group by death, resignation or retirement. The total number of ex-radiation workers is dependent on the leaving rate. From the records of the National Radiological Protection Board (NRPB) and from informal discussions with employers, we have arrived at a figure of between 5 and 10% for the annual percentage of workers who cease radiation work other than by death or retirement. We have considered 5 and 10% which, under steady state conditions, lead respectively to 171 000 and 330 000 living ex-workers. We have assumed also that those leaving radiation work do not return to it within the latent period of risk following their last exposure.

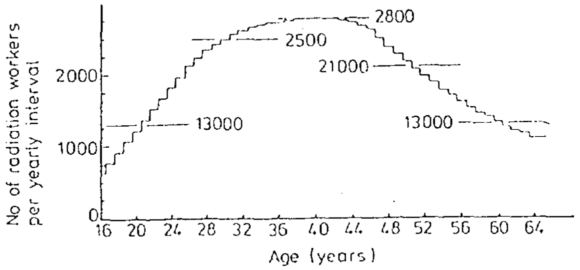

Fig. 1. The age distribution of the work force used throughout this paper.

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2.2. *Natural death rates*

Table 1 shows the Registrar General's figures (for 1972) on which we have based our non-radiation-induced deaths. We have considered 'all-cancers' (ICD 140-239 inclusive) and leukaemias (ICD 204-207 inclusive) in our comparisons of natural incidence with radiation-induced incidence. A specific group of workers would have a standardized mortality ratio (SMR) to account for selectiveness of employment (e.g. a requirement to be medically fit) and this may be accounted for as described in sections 2.3 and 3.1. The SMR is simply the ratio of the death rate (from a given cause) in a specific group to that in the whole population.

Table 1. The Annual Death Statistics used in this work for comparison purposes (Registrar General 1972)

Age group	% deaths (all causes)	% deaths (all cancers) (ICD 140-239)	% deaths (leukaemias) (ICD 204-207)
16–25	0·092	0·0096	0·0023
26–35	0·096	0·0172	0·0021
36–45	0·227	0·0502	0·0030
46–55	0·733	0·1899	0·0049
56–65	2·08	0·6094	0·0121
66–75	5·42	1·3624	0·0250
76–85	12·39	2·1569	0·0453
86–95	25·57	2·4963	0·0691

2.3. *The risk of death from radiation*

Three factors determine the radiation-induced death rate:

(i) the annual exposure,
(ii) the total risk per unit exposure, and
(iii) the latent period of the risk.

It is convenient to work with an exposure to each worker of 1 rad/year and to apply a scaling factor to find the effects due to other average exposure levels (see below).

The choice of data for factors (ii) and (iii) has required judgement based on an assessment of other studies of populations exposed to radiation. These studies indicate that the rate of radiation-induced cancer death varies considerably with time after exposure. The largest group of people studied over a long period are the 23 979 Japanese survivors with exposures above 10 rad who are included in the life-span study of the Atomic Bomb Casualty Commission (Jablon and Kato 1971). In this group the excess leukaemia rate has decreased slowly with time since the mid 1950's and it may be predicted that all the radiation-induced leukaemias will have occurred by the mid 1970's (Goss 1974). This leads to a risk coefficient of 30 per 10^6 man rad for radiation-induced leukaemia death. Excess mortality from all other cancers (excluding leukaemia) follows a different time pattern. After a very low rate during the 5-year period 1955–60, the mortality rose in the next two 5-year periods. From

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these data it is not possible to predict the eventual shape of the time distribution of the cancer rate. To estimate the absolute risk of radiation-induced cancer death, Goss doubled the number of excess cancers which had occurred up to 1970. This leads to a risk coefficient of 70 per 10^6 man rads and hence to a total of 100 per 10^6 man rads for all cancers (including leukaemia). These figures apply to gamma radiation.

Risk coefficients obtained from the study of other irradiated groups are not easily related to the conditions of whole body exposure experienced by the occupationally exposed workers of interest to us. For example, radiotherapy patients such as ankylosing spondylitics (Court Brown and Doll 1965) and those treated for metropathia haemorrhagica (Smith and Doll 1976) receive high and localized exposures which are very dissimilar to those of our group and hence may have a quite different excess cancer pattern. Also, those exposed are a special group who may exhibit abnormal medical response to the exposure whereas we are concerned with a predominantly healthy group. Studies of the radiologists in the USA (Matanoski, Seltser, Sartwell, Diamond and Elliott 1975) are probably the most comparably exposed group to the classified workers in our study, but unfortunately their doses are not recorded and so risk coefficients cannot be deduced, neither is it possible to extract the time pattern of their excess cancers.

For the purposes of the present paper it is proposed to use a figure of 100 cancer deaths per 10^6 man rads (10^{-4} per rad), based on the Japanese survivor data corrected for gamma-ray exposure only. With the same justification we use a risk coefficient of 30 per 10^6 man rads (3×10^{-5} per rad) for excess leukaemias. These figures may be regarded as conservative estimates when applied to the low doses received at low dose rates by radiation workers. Biological repair mechanisms will act to reduce radiation damage to tissue to below that expected from high dose rate observations. This may be taken into account by a protraction factor but our knowledge of low dose rate effects is inadequate to establish a value for this factor so it will be assumed that the risk is linearly related to the dose for the range of doses accumulated by radiation workers. So for example, 1 rad accumulated by each of 10^6 persons will lead to the same number of cancer deaths as 100 rad to each of 10^4 persons.

The time variation of the number of excess cancer mortalities following exposure is not clear from the currently available evidence and so we have made an arbitrary choice for our calculations. We have assumed that the risk occurs over a limited period rather than remaining at a high value for all times after exposure. The Japanese data indicate an increased leukaemia risk lasting about 30 years and a simple assumption is that the risk remains constant over the period 5–30 years after exposure. For all cancers the risk appears to exist for a longer time and it is assumed constant from 5 to 50 years. In order to test the sensitivity of our results to the assumed form of the risk with time, we have considered three forms of risk-in-time following exposure:

A, a rectangular distribution,
B, a Gaussian distribution, and
C, a sharply peaked distribution—all the risk during the 11th year.

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Fig. 2 displays these time distributions. Calculations have been performed with A and B spread over 50 years as well as 30 years as in the figure and these are distinguished as A_{30}, A_{50}, etc. This permits some estimate of the difference between leukaemia deaths—all of which may be expected to have occurred within 30 years—and other cancer deaths where the risk may spread over a longer period following exposure.

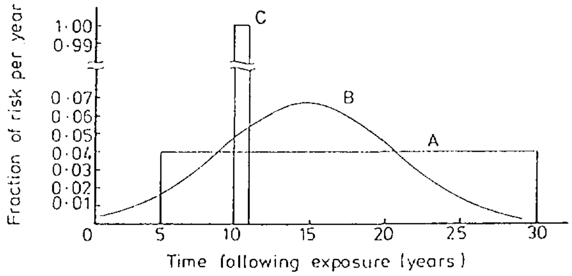

Fig. 2. The three risk-time relations A_{30}, B_{30} and C_{11}. We also consider A_{50} and B_{50} (i.e. the same form as A_{30} and B_{30} but spread over 50 years).

Having established the three factors (i), (ii) and (iii) we may now calculate the expected age-specific radiation-induced deaths in our work force. The numbers of workers in each 10-year age group are shown in column B of tables 2 and 3 and the corresponding 'non-radiation' deaths in columns C, D and E. Columns F and G are calculated by summing a man's risk of dying in any particular year arising from each year of exposure up to that time. Hence we calculate the number of deaths in a group of the same age and exposure. This is repeated for all age and exposure groups and the results summarized in columns F and G. Both columns F and G (A_{30} and A_{50} respectively) have been evaluated with a risk coefficient of 10^{-4} per rad so to find the expected number of radiation-induced leukaemia deaths we must scale column F appropriately (see eqn 1).

While the age-specific numbers of radiation-induced deaths shown in tables 2 and 3 are applicable to a population of 100 000 workers each exposed to 1 rad/year with an associated risk of 10^{-4} per rad, we can deduce the corresponding numbers for any other parameters from

$$M = m \times \frac{P_w}{10^5} \times \frac{R}{10^{-4}} \times D = mP_w RD/10 \qquad (1)$$

where m is the number of deaths shown in the table, P_w is the working population, R is the risk per rad and D is the average annual dose per worker. This simple scaling is possible because of the negligible effect of radiation-induced deaths on the population distribution.

The calculations described are for the steady state and it would take 50 years for the exposure distribution to be reached. Since this is longer than the nuclear power industry has been in existence, it is of interest to consider the approach to the steady state situation. We have maintained the same work

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Table 2. Summary of annual deaths—5% leaving rate. The age-specific death rates in our steady state population of radiation workers and ex-workers. Columns C, D and E show the numbers of deaths expected among non-radiation workers on the basis of table 1. Columns F and G show the predicted numbers of radiation induced deaths on the basis of $R = 10^{-4}$ rad^{-1} and $D = 1$ rad/year for risk type A over 30 years (F) and 50 years (G). Note: to find the expected number of radiation-induced leukaemia deaths, column F should be scaled by eqn (1) with an appropriate R (e.g. 3×10^{-5}).

A	B			C			D			E			F			G		
	Population size			All ICD nos. (all causes)			ICD (204-207) (leukaemias)			ICD (140-239) (all cancers)			Radiation-induced cancers A_{30}			A_{50}		
Age	IN	Total	EX	IN	Total	EX	IN	Total	EX	IN	Total	EX	IN	Total	EX	IN	Total	EX
16–25	13 000	15 000	2 000	12	14	2	0	0	0	1	1	0	0·02	0·03	0·01	0·01	0·02	0·01
26–35	25 000	37 000	12 000	24	35	11	1	1	0	4	6	2	0·30	0·50	0·19	0·17	0·28	0·11
36–45	28 000	53 000	25 000	63	119	56	1	2	1	14	26	12	0·75	1·44	0·69	0·41	0·80	0·38
46–55	21 000	57 000	36 000	156	420	264	1	3	2	40	109	68	1·00	2·23	1·23	0·57	1·33	0·76
56–65	13 000	52 000	39 000	274	1 093	819	2	6	5	80	320	240	0·85	2·06	1·21	0·54	1·56	1·02
66–75			38 000			2 069			10			520			1·16			1·19
76–85			16 000			2 035			7			354			0·27			0·41
86–95			3 000			701			2			68			0·02			0·04
16–65	100 000	214 000	114 000	529	1 682	1 153	4	12	8	140	463	323	2·93	6·26	3·33	1·71	3·99	2·28
16–95	100 000	271 000	171 000	529	6 487	5 958	4	31	26	140	1 406	1 266	2·93	7·70	4·77	1·71	5·62	3·92

[redacted]

Table 3. Summary of annual deaths—10% leaving rate

A	B			C			D			E			F			G		
	Population size			All ICD nos. (all causes)			ICD (204-207) (leukaemias)			ICD (140-239) (all cancers)			Radiation-induced cancers A_{30}			A_{50}		
Age	IN	Total	EX	IN	Total	EX	IN	Total	EX	IN	Total	EX	IN	Total	EX	IN	Total	EX
16–25	13 000	17 000	4 000	12	16	4	0	0	0	1	2	0	0·01	0·03	0·02	0·01	0·02	0·01
26–35	25 000	48 000	23 000	24	47	23	1	1	0	4	8	4	0·19	0·50	0·31	0·10	0·28	0·17
36–45	28 000	78 000	50 000	63	175	113	1	2	1	14	39	25	0·40	1·44	1·04	0·22	0·80	0·58
46–55	21 000	93 000	72 000	156	685	528	1	5	4	40	177	137	0·49	2·23	1·74	0·27	1·33	1·06
56–65	13 000	92 000	79 000	274	1 912	1 638	2	11	10	80	560	480	0·38	2·06	1·68	0·22	1·56	1·34
66–75			68 000			3 679			17			924			1·16			1·19
76–85			29 000			3 618			13			630			0·27			0·41
86–95			5 000			1 245			3			122			0·02			0·04
16–65	100 000	328 000	228 000	529	2 834	2 305	4	19	15	140	786	646	1·47	6·26	4·79	0·83	3·99	3·16
16–95	100 000	430 000	330 000	529	11 377	10 848	4	53	49	140	2 462	2 322	1·47	7·70	6·23	0·83	5·62	4·80

force but with no initial exposure and no ex-workers with radiation exposure. The steady state exposure pattern and ex-worker distribution is built up by calculating the annual number of radiation deaths for each year up to 50 years. The results are summarized in fig. 3 and table 4.

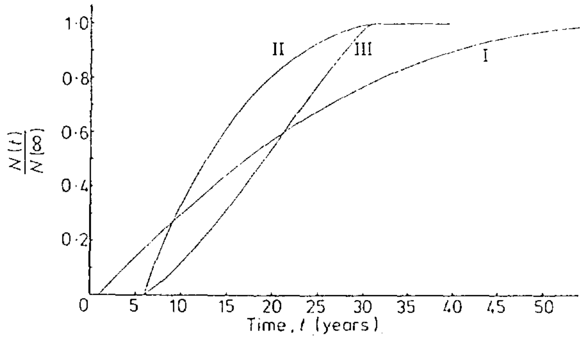

Fig. 3. The growth to steady state. Curve I represents the growth of the number of ex-workers with radiation exposure. Curve II is the growth of the expected number of radiation-induced cancer deaths among in-service workers and curve III among ex-workers. $N(t)$ is the number in year t and $N(\infty)$ the number in the steady state as in table 2, column A.

Table 4. Showing the accumulated number of radiation-induced deaths in 5-year intervals following time zero when radiation exposure began. Also shown is the number of people involved for our standard 100 000 workers exposed to 1 rad/year each and for 3000 workers exposed to ½ rad/year each

	Time (years)				
	10	15	20	25	30
Working population 100 000 (1 rad/year)					
Total workers IN + EX	150 861	175 749	197 542	216 279	231 905
Accumulated RI deaths A_{30}	4	17	38	67	103
Working population 3000 (½ rad/year)					
Total workers IN + EX	4 526	5 272	5 926	6 488	6 957
Accumulated RI deaths A_{30}	0·06	0·25	0·57	1·0	1·5

3. Observation time

3.1. *Time required for a survey*

We are interested in an estimate of the number of years over which cancer deaths among radiation workers must be observed to show a significant difference between them and a corresponding group of non-radiation workers.

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We will assume that we can find an appropriate control population and that it is identical to the radiation work force except that it is not occupationally exposed to radiation. In practice it will probably be necessary to draw the control group from among those radiation workers with the lowest exposures. In this way we can be sure that the control and the exposed populations have been subjected to the same selection procedures.

We must consider the confidence that we will be able to place on the rejection of the null hypothesis (that there is no risk involved in exposure to radiation and consequently that the mean numbers of cancer deaths will be equal in the control and exposed groups). This is normally assessed as a significance level α, defined such that α is the probability that we will *reject* the null hypothesis when it is *true*. The corresponding confidence limit is expressed as a percentage and is $(1-\alpha)\times 100$.

We must also consider the power of the test we apply to the acceptance or rejection of the null hypothesis. The power $(1-\beta)$ of a test is defined such that β is the probability that we will *accept* the null hypothesis when it is *false*.

Formulating the significance level and the power of the test as in Armitage (1971), we find that the observed mean number of excess cancer deaths ($\delta\bar{x}$) is significant at the $P\%$ level ($P = 100\alpha$) if

$$\delta\bar{x} > U_{1\alpha}\,\sigma\,\sqrt{(2/n)} \tag{2}$$

where $U_{1\alpha}$ is the standardized normal deviate exceeded in the positive direction with probability α, σ is the standard deviation of the population mean (taken to be the same in exposed and control groups) and n is the number of observations which, in our case, is the number of years, since there is one 'observation' per year. A difference in the number of cancer deaths between the two groups will be detected with a probability $1-\beta$ if the true mean difference ($\delta\mu$) satisfies

$$\delta\mu > (U_{1\alpha}+U_{1\beta})\,\sigma\,\sqrt{(2/n)}. \tag{3}$$

If we now put $\delta\mu = m$, the true number of radiation-induced cancers, and rearrange eqn (3) we have an expression for the time required for a survey to have probability $1-\beta$ of rejecting the null hypothesis at the α significance level:

$$n > 2(U_{1\alpha}+U_{1\beta})^2\sigma^2/m^2. \tag{4}$$

In these expressions σ^2 (the variance) has been taken to be equal to the mean number of non-radiation-induced cancer deaths; that is, we have assumed a Poisson distribution.

Table 5 has been compiled to show values of n for $\alpha = 0{\cdot}05$ and $0{\cdot}2$, $\beta = 0{\cdot}5$ and m as given in table 2, column F; that is, the times necessary to have a 50% chance of showing a positive radiation risk at the 5% and 20% significance levels. The values in this table may be interpreted another way. Rearranging eqn (2) with n on the left hand side, we see that, if after n years the observed mean excess cancer deaths are as in table 2, column F, the survey shows positive radiation risk at the 5% (or 20%) level. This is an appropriate interpretation once the survey is running since we will then have an observed mean difference and will ask what is its significance.

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Table 5. The number of years needed to demonstrate at the 5 and 20% significance levels that there is a positive risk from occupational radiation exposure if the observed mean number of excess cancers are actually at the level we calculate. (Blanks signify > 10 000 years.) These numbers may be scaled to other situations using eqn (5)

	A_{30}						B_{30}						C_{11}					
Significance level	20%			5%			20%			5%			20%			5%		
Age groups	IN	All	EX	IN	All	EX	IN	All	EX	IN	All	EX	IN	All	EX	IN	All	EX
16–25	3 545	1 575	—	—	6 011	—	886	567	—	3 381	2 164	—	—	—	—	—	—	—
26–35	63	34	79	241	130	300	35	20	49	135	77	188	10	5	10	37	20	40
36–45	35	18	36	135	68	136	21	11	24	81	42	90	9	6	18	35	23	68
46–55	57	31	64	216	119	243	40	26	64	153	101	243	23	23	87	88	86	334
56–65	157	107	232	599	408	887	123	109	292	470	416	1 113	92	133	621	351	506	2 372
16–65	23	17	41	88	64	158	16	13	39	60	51	149	8	10	42	31	37	161
16–95	23	34	79	88	128	301	16	29	82	60	112	314	8	24	74	31	92	284

The number of years (N) required to show a positive contribution of radiation exposure to cancer death rates for a specific population, risk level and dose rate may be found by scaling the appropriate n in table 5 using eqn (5) (which includes the SMR value so that the effect of known variations in natural death rates on N may be estimated).

$$N = n \times \text{SMR} \times \frac{10^{-8}}{R^2} \times \frac{1}{D^2} \times \frac{10^5}{P_w} = \frac{n \times \text{SMR}}{R^2 D^2 P_w} \times 10^{-3} \text{ years.} \qquad (5)$$

3.2. *Risk coefficients detectable in a given time*

Rearranging eqn (5) we see that

$$R = \left(\frac{n}{N} \frac{\text{SMR} \times 10^{-3}}{D^2 P_w}\right)^{\frac{1}{2}}. \qquad (6)$$

Thus, using the values of n from table 5 and putting N years as the observation time, the lowest detectable risk coefficients may be found and some examples of these are shown in table 6.

There is a one to one correspondence between the true number of excess cancer deaths and the radiation risk coefficient. However, since the observed excess cancers are the difference of two statistically fluctuating variables the corresponding risk coefficient can only be established to lie within a range of values. To give some indication of the magnitude involved in trying to establish risk coefficients we have shown, in the four right hand columns of table 6, the 95% confidence interval of the risk coefficients which corresponds to observed radiation cancer deaths equal to those predicted in table 3. We should emphasize that columns 2–5 in table 6 are independent of our calculated number of radiation-induced cancer deaths while columns 6–9 are based on our predicted values.

3.3. *Other influences*

The risk values detectable and the times required for a survey to yield a positive identification of radiation risk as presented in this paper are subject to variations not covered by our statistical analysis. Systematic differences between the control and the exposed group or from one year to another can be incorporated in the SMR (see section 2.2) but it is unlikely that these are known. The effect is an additional spread on the natural cancer deaths and hence an increase in the required observation time. Another factor is the classification of a cancer death as in-service or ex-service (for example, if the cancer has influenced retirement). This suggests the desirability of not discriminating and supports the argument for full follow-up studies.

The effects of exposure to radiation for medical diagnostics or therapy must be omitted from the study because of the practical difficulties involved. Dose measurements of exposure to radiation for medical purposes are not made routinely and if they were they would be treated as sensitive confidential information. Even if a satisfactory assessment of doses were available, because

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Table 6. The minimum risks (at the 5% significance level) of death due to radiation-induced leukaemia (ICD 204-207) or from any form of cancer (ICD 140-239) by a survey covering 214 272 in-service and ex-workers in the age range 16–65 years. Scale using eqn (6). Also showing the 95% confidence interval (one-sided) on the value of the risk if the observed difference between the control and the exposed are as in columns F of tables 2 and 3. Where the observation time is less than shown necessary in table 5, the lower limit is negative but for physical reasons it is put to zero. Column 6 and 8 show the residual probability that the risk is not positive finite

	Minimum detectable risk (per 10^6 man rads)				95% confidence values of risk (per 10^6 man rads)			
	Leukaemia		All cancers		All cancers			
Leaving rate	5%	10%	5%	10%	5%		10%	
Observation time (years)					Probability of $R = 0$	Risk	Probability of $R = 0$	Risk
1	129	162	800	1 042	40%	0–900	44%	0–1 142
10	41	51	253	329	26%	0–353	31%	0–429
25	26	32	160	208	15%	0–260	21%	0–308
50	18	23	113	147	7·3%	0–213	13%	0–247
100	13	16	80	104	2·0%	20–180	5·7%	0–204

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they are localized it would be difficult to relate them to the uniform whole body doses experienced occupationally. Furthermore, individuals would be reluctant to cooperate in a survey which collected information which could prejudice their employment prospects. Medical exposures have to be considered as background and we must presume some cancellation since they are equally probable in exposed and control groups. Over a very long survey time, the presumed cancellation of all background effects becomes more acceptable.

4. Results and discussion

In table 2 we have shown the number of radiation-induced cancer deaths that would occur in the population (columns A and B) if the risk was 10^{-4} per rad distributed in time as A_{30} (column F) or A_{50} (column G). The longer latent period permits a greater influence of the normal death rate and results in a smaller number of radiation-attributed deaths. Since there is no striking distinction to be drawn between the effects of using A_{30}, B_{30} or C_{11} we have not reproduced the details here. Corresponding to the 7·7 total radiation-induced cancer deaths in column F for A_{30}, we calculated 8·23 for B_{30} and 9·11 for C_{11}. The increase through A_{30}, B_{30} and C_{11} is due to the concentration of the risk into a shorter period hence allowing radiation-induced death instead of 'natural' death slightly more often.

Comparing columns E and F we see that the 7·7 radiation cancer deaths are against a background of 1406 other cancer deaths and this is a clear indication of the detection difficulties to be faced. A 30-year latent period is appropriate for leukaemia while death from all other forms of cancer may occur up to 50 years following exposure. Thus to find the number of radiation-induced leukaemia deaths expected we should scale the figures in column F using R (leukaemia) $= 3{\cdot}0 \times 10^{-5}$ (see section 2.3). For example, how many deaths from leukaemias compared to all-cancers would we expect in a particular industry employing 3000 radiation workers each receiving an average dose of 0·5 rad/year? Using eqn (1) and table 2, we predict that the number of leukaemia deaths per year is 0·034 (distributed among 3000 workers and 5149 ex-workers) compared with 0·93 expected naturally; correspondingly there would be 0·08 cancer deaths compared with 42 naturally. Thus in a period of 25 years we would expect in the industry 24 leukaemia deaths (3 in-service) of which 0·8 (0·3 in-service) would be radiation-induced; in the same time period we would expect 1056 (105 in-service) cancer deaths of which 2 (0·6 in-service) would be radiation-induced.

Probably the most significant feature of table 2 is the balance of deaths between in-service and ex-workers. Any long time effects will be lost unless adequate provision for follow-up exists. For A_{30} risk 62% of all radiation-induced deaths will be among ex-workers.

Table 3 shows all the quantities described in table 2 but for a leaving rate of 10% instead of 5%. Comparison of the corresponding columns in tables 2 and 3 show the same number of age-specific radiation-induced deaths but distributed more heavily towards the ex-workers in the 10% case; for A_{30}, 81%

of all radiation-induced deaths will be among ex-workers. More significantly, we see that in table 3 we have a background of all-cancers of 2462 which seriously reduces the chance of detecting the effect of radiation on the death rate. In our estimates of the time necessary for the survey, we optimistically work with table 2, that is assuming a 5% leaving rate. In the nuclear power industry at least, this is a realistic figure.

Since the nuclear power industry is only 25 years old—i.e. less than the latent period—we are not yet in the steady state situation. Fig. 3 shows the growth period of the effect of radiation, the number of induced deaths reaching the steady state value after 30 years because of the use of A_{30}. The ex-worker numbers require 80 years to reach steady state. In table 4 we see the accumulated number of radiation-induced deaths at 5-year intervals following the start of radiation work. We have included in this the corresponding figures for a working population of 3000 and also the total number (IN and EX) of workers at that time. So we see that in the first 25 years we would expect considerably less than the 2 radiation-induced cancer deaths predicted in a 3000 work force—table 4 shows 1 death but that is for A_{30}—taking a 50-year latent period (A_{50}) we would expect 0·6 deaths due to radiation in the first 25 years. Since we are interested in conservative estimates we shall restrict further discussion to the steady state situation.

Table 5 shows how many years are necessary before a survey on our work force has a 50% chance of confirming a positive risk from radiation exposure to the 5 and 20% significance levels. It is clear from tables 2 and 3 that follow-up studies are essential and while table 5 gives emphasis to this it also clarifies the relative merits of looking at specific groups. The most obvious deduction from table 5 is that the analysis of the survey data should be restricted to those workers and ex-workers below retirement age. The large background of natural cancer deaths above the age of 65 serves only to spoil the resolution. The optimum on these figures is an analysis of 16–55 for which the time required is 11 years (20% significance) and 44 years (5% significance); however, the influence of the assumed latent period becomes important and 16–65 is probably safer.

Comparing A_{30} and B_{30} in table 5 we see only marginal differences overall and although C_{11} requires significantly shorter survey times for the lower age groups it is not a realistic form for the risk-time relation.

In table 6 we show the magnitude that the risk coefficient must be before it can be detected as positive against statistical fluctuations. The second part of table 6 shows the range of risk coefficients compatible with the observed mean annual number of radiation-induced deaths being those predicted in column F of table 2. Until the observation time is greater than that in table 5, a negative risk is compatible with the observation and since we do not permit this possibility, we show the residual probability that the risk is not positive (expressed as a percentage).

Tables 5 and 6 taken together demonstrate the difficulties to be faced in analysing the results of a survey of the causes of death of occupationally exposed radiation workers.

5. Conclusions

The proportions of induced cancer deaths shown by tables 2 and 3 show clearly the need for follow-up studies of the causes of death of ex-radiation workers to supplement the records of actual workers. Moreover, we consider the proportions shown in these tables to be a lower limit as systematic factors will tend to bias towards ex-workers deaths through a greater concentration of ill-health among those leaving. Since these factors are unquantifiable it seems wise to concentrate on the total (age-specific) deaths in any analysis. We see also (particularly from table 5) that the exclusion of the over 65's enhances the possibility of drawing conclusions. So we suggest that the analysis should concentrate on all radiation workers and ex-radiation workers between 16 and 65 although all included in the survey would be followed until death.

This paper shows that if a large survey (100 000) on occupational exposure is made the first conclusions would not be expected for at least 20 years. However, if total exposures are much less than 100 000 man rad/year or if the risk is less than 100 per 10^6 man rads—the time required to prove a positive effect of radiation on the incidence of deaths from cancer becomes very high and with little prospect of making statistically valid intermediate statements.

Although these prospects seem discouraging a survey has valuable contributions to make. Firstly, if the risk levels for low dose exposures are much higher than those anticipated, this will become evident at a much earlier stage than suggested in table 5. For example, a factor of 3 increase in the risk reduces the time required by a factor of 9 (see eqn 4) so the effects of radiation would be detectable at the 5% significance level in under 10 years (and within 2 years at the 20% level). Although it is most unlikely that the actual risk is higher than the expected risk, the establishment of a reliable base of data will provide the means to refute or ultimately to justify current estimations of levels of risk. Secondly, a national survey may identify a rare form of cancer which can be radiation induced but which would be insignificant in data relating to small groups of radiation workers. While such cancers would account for a very small number of deaths, if they existed it would indicate environments where the working procedures should be reviewed. Analysis of any cancers which have low natural incidence would also provide an index against which the significance of the incidence of the cancer in particular industries may be assessed. Finally, any overall reduction in life expectancy for radiation workers may be investigated when sufficient data have been collected.

Résumé

L'observation et l'analyse des décès par tumeurs cancéreuses parmi les techniciens exposés aux radiations

La politique énergétique mondiale future dépend dans une certaine mesure de l'effet qu'a sur la mortalité cancéreuse le degré d'irradiation auquel les techniciens sont exposés. De là dépend aussi la décision prise sur les dépenses à prévoir pour réduire les niveaux d'irradiation éprouvés par les techniciens. L'exposé discute certaines difficultés d'analyse de la situation et il présente les résultats de calculs estimant les mortalités par irradiation auxquelles on peut s'attendre pour chaque groupe d'âges particulier, de toutes les tumeurs cancéreuses induites ainsi que, séparément,

de la leucémie. En utilisant une forte valeur pour l'irradiation professionnelle moyenne, et une estimation prudente du risque connexe, nous trouvons qu'il faut étudier pendant de nombreuses années la mortalité parmi les techniciens d'irradiation avant d'accumuler assez de données pour différencier les effets des néoplasmes induits par les rayonnements de ceux provenant d'autres causes. Nous montrons qu'il est judicieux de déterminer la cause des décès de personnes restant employées dans l'industrie aussi bien que de toutes celles qui s'y engagent et la quittent par la suite, après une courte durée éventuelle d'emploi. Nos évaluations sont basées sur le maintien d'une dose d'irradiation professionnelle déterminée par personne et par an au cours d'une période d'étude pouvant s'étendre sur plusieurs décennies. Cependant il est facile de ramener à une échelle commune tout autre taux d'irradiation.

L'exposé donne aussi des évaluations des plus faibles coéfficients de risque pouvant être détectés pendant une durée donnée d'observation. Comme, pour un effectif de 3000 ces plus faibles valeurs détectables sont d'un plus grand ordre de grandeur que ceux auxquels on s'attendait, il est clair que seule une étude nationale ou internationale peut donner assez de renseignements pour atteindre même les plus modestes objectifs.

ZUSAMMENFASSUNG

Beobachtung und Analyse tödlicher Krebsfälle unter Arbeitern, die berufsmässig der Strahlengefahr ausgesetzt sind

Das Ausmass, in dem Strahlungsgefahr am Arbeitsplatz zu tödlichen Krebsfällen beiträgt, beeinflusst die künftige Weltenergiepolitik. Es bildet ebenfalls einen Faktor bei der Entschiedung über die Kosten, die zur Reduzierung der Strahlenmenge am Arbeitsplatz aufgewandt werden sollten. In diesem Rahmen erörtern wir einige der Schwierigkeiten bei der Situationsanalyse und stellen die Ergebnisse von annähernden Berechnungen über die zu erwartende, altersbedingte Strahlungssterblichkeit aufgrund aller induzierter Krebsarten bzw. Leukämie. Unter Verwendung eines hohen Faktors für die berufsbedingte Exposition und einer zurückhaltenden Einschätzung des damit verbundenen Risikos kommen wir zu dem Ergebnis, dass sich eine Untersuchung der Sterblichkeit von strahlungsexponierten Arbeitern über lange Jahre erstrecken muss, da erst dann genügend Daten zur Verfügung stehen, um festzustellen, welche Neoplasmen durch Strahleneinwirkung oder andere Ursachen gebildet werden. Wir belegen die Ratsamkeit, nicht nur die Todesursache solcher Arbeiter festzustellen, die in der Industrie geblieben sind, sondern auch derer, die nur vorübergehend—wie kurz auch immer—in der Industrie beschäftigt waren. Unsere Berechnungen basieren auf der Aufrechterhaltung der berufsmässig bedingten Bestrahlungsdosis pro Person und Jahr über den Zeitraum der Untersuchung, die sich über mehrere Jahrzehnte erstrecken könnte. Allerdings lässt sich eine Umrechnung der eventuell veränderten Dosis leicht durchführen.

Wir liefern darüberhinaus Berechnungen der Minimalrisiko-Koeffizienten, soweit sie sich in einer vorgegebenen Beobachtungszeit feststellen lassen. In Anbetracht der Tatsache, dass bei einer Arbeiterzahl von 3000 diese geringsten, messbaren Werte von einer Grössenordnung waren, die die Erwartungen übertraf, ist klar, dass nur eine nationale oder internationale Untersuchung die Daten produzieren kann, die selbst geringen Ansprüchen Genüge tun.

Резюме

Наблюдения и анализ смертей от рака среди персонала, работающего в секретных условиях с радиацией

Та степень, в которой воздействие радиации в условиях работы, способствует смертности от рака влияет на будущее энергетическое развитие всего мира. Она также является фактором, определяющим расходы, направленные на сокращение уровней радиации, которой подвергается персонал. В этой статье мы рассматриваем некоторые трудности в анализе ситуации и представляем результаты расчетов, дающих оценку предполагаемой смертности от возрастаспецифической радиации для всех случаев вызванного рака и белокровия отдельно. Взяв высокое значение среднего воздействия радиации на персонал и заниженную оценку связанного риска, мы обнаружили, что для сбора полных данных, определяющих возникновение неоплазм, вызываемых радиацией или другими причинами, потребуется многолетний обзор смертности среди работников, связанных с радиацией. Мы показали, что желательно определять причину смерти как для работников, продолжавших работать в этой области, так и для работников, покинувших эту область, проработав в ней возможно лишь короткое время. Наши оценки основаны на поддержании дозы радиации в радах на одного человека в

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год в течение периода проведения наблюдений, который может продолжаться несколько десятилетий. Однако масштаб этих оценок может быть легко изменен для любой другой дозы.

Мы также определяем коэффициенты наименьшего риска, выведенные за определенно время наблюдения. Поскольку для персонала в 3000 человек эти наименьшие выведенные значения во много раз превышают предполагаемые, ясно, что только государственный или международный обзор может установить данные, достаточные даже для скромных целей.

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