PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Radiological Criteria for the Disposal of Solid Radioactive Wastes [and Discussion]

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Radiological criteria for the disposal of solid radioactive wastes

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Radioactive waste disposal is only one cause of exposure to ionizing radiation. Criteria for control should fit into the world-wide system for protection against radiation hazards, developed by the International Commission on Radiological Protection over the past 50 years.

The system is simple and logically inevitable for any non-threshold pollutant. It consists of limits to protect individuals against unacceptable risks and a requirement to reduce the overall impact of the source causing the radiation to a level that is 'as low as reasonably achievable'. Particular aspects examined in the paper include the long timescales of concern and the role of comparisons with natural levels of radiation.

The output of radiological assessment is an input to broader decisions on waste management, accommodating environmental pressures within political judgements. It is necessary to pursue the scientific analysis of waste disposal so that the results can be used as a firm foundation to confront, openly and honestly, the concerns of the public and of the politicians.

1. Introduction

This paper is aimed more at the title of the session, 'Overview and perspective', although it covers in the process 'Radiological criteria'. The views expressed, especially towards the end, are those of the author and not necessarily those of the Board.

2. Radiation effects

The basis for radiation protection is that exposure of humans to radiation produces undesirable effects. This is not a matter for dispute at high radiation doses that give direct effects ranging from erythema through to death within minutes. All of these direct effects have two characteristics: they are always seen in the exposed individual, making allowance for variations in tolerance and other factors, and they have an operational threshold below which they are not seen. These direct effects are referred to as 'non-stochastic'. Radiation is similar to other toxins in the characteristics of production of these direct effects.

Undesirable effects in the other class are more subtle, and can only be detected by statistical techniques. The two major categories of these indirect effects are cancer induction and the production of hereditary changes. The main characteristics of these effects are that a particular individual exposed to radiation may, or may not, manifest the effect, although in a large exposed population a certain number will be observed to do so, and that there is a considerable latent period between irradiation and manifestation. There are significant differences in our knowledge of the two major categories of effect.

Cancer induction has been observed in human populations of various types in a range of circumstances; however, we know very little about the induction mechanism, the role of radiation or the possible interaction with other causal agents. The types of cancer induced are quite variable; the prognosis is a function of both the type and the level of development of medical treatment.

Hereditary effects of radiation have not been observed in human populations but have been studied in faster-breeding species such as small mammals and lower organisms. There is a reasonably developed body of knowledge of how genetic characteristics are passed from one generation to the next and a plausible mechanism by which radiation could cause damage that could be transmitted onwards. None the less, quantitative estimates of the increase in genetic changes induced by radiation are based on observed frequencies in other organisms and a presumed increment on the pre-existing frequences in man (UNSCEAR 1982).

For both these categories of effect the major bases for the protection system are assumptions, believed by the scientific community to be plausible and tenable, but assumptions none the less. The two assumptions of most practical consequence are that an increment in radiation dose causes an increment in frequency of effect manifestations – linearity – and that this relation holds down to the lowest doses – no observed threshold. Superimposed on these assumptions are a number of scientifically based extrapolations used to produce the numerical estimates of cancer induction or hereditary damage expressed as frequencies per unit dose in various organs, or as a function of sex, or age at irradiation, etc. The results from all this are the highly simplistic risk factors used in consequence calculations, given as frequencies of serious radiation-induced effects of $1.25 \times 10^{-2}\ \mathrm{Sv}^{-1}$ for cancer induction, $1.65 \times 10^{-2}\ \mathrm{Sv}^{-1}$ including genetic effects in the first two generations, or $2.05 \times 10^{-2}\ \mathrm{Sv}^{-1}$ including all future genetic effects. The discussion of the bases for these estimates should indicate that it is not unreasonable to round all of them off to $10^{-2}\ \mathrm{Sv}^{-1}$ and explain the authors' lack of interest in discussions centring on factors of two.

3. Sources of radiation

Although this meeting is concerned with the specific subject of waste disposal, it is worth while to set this into the context of a radiation-permeated world. There are two main points: that we are all inescapably exposed to natural radiation and natural radioactivity and that the major cause of clearly man-made exposure is medical uses of radiation. A summary of the current levels of exposure of the population of the U.K. is given in table 1 (Hughes & Roberts 1984). Although table 1 is scientifically accurate it does not illustrate two important aspects:

Table 1. Summary of the current levels of radiation exposure of the population of the U.K. from all sources

source	annual collective dose/(man Sv)	average annual dose/μSv
natural		
cosmic	16800	300
terrestrial gamma	22400	400
internal irradiation	20700	370
radon	39000	700
thoron	5600	100
artificial		
medical	14000	250
miscellaneous	600	11
fallout	580	10
occupational exposure	510	9
radioactive waste disposal	100	2
total (rounded)	120000	2150

firstly, variations in exposures of individuals are very large and the variability differs between the components; secondly, this is a summary of the present situation so that there is no dose attributed to radioactive waste currently in store, undergoing treatment or to material not yet even designated as waste. The component shown as radioactive waste is only that from effluent discharges.

4. The control system for radiation

The discovery that radiation could have harmful effects was made quite soon after the discovery of the phenomenon of radioactivity. The International Commission on Radiological Protection was formed in 1928 during the Second International Congress of Radiology and the membership is still subject to approval at the meetings of that Congress. Most of the early applications of radiation were in the medical area and the early ideas of protection also developed in this area (IXRPC 1934). It was perhaps because of the international nature of medicine that the control systems recommended by the ICRP were accepted internationally in the first instance. It will only be because the recommendations are sensible and fulfil a need that they continue to be accepted internationally.

The very early recommendations of ICRP were based primarily on the limitation of dose rates to those using radiation to levels that did not produce direct effects. However, since before the development of nuclear power, the aim of radiation protection has been to prevent direct effects and to limit the probability of indirect effects (called 'stochastic' by ICRP) to levels deemed acceptable (ICRP 1955). The mechanism for achieving this aim is embodied in the system of dose limitation recommended by the ICRP (1977):

(*a*) no practice shall be adopted unless its introduction produces a positive net benefit;

(*b*) all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account; and

(*c*) the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission.

This system applies to all the sources of radiation referred to earlier. ICRP had its foundation in the control of medical exposures and these are still a highly important facet of its work. The only part of the system that does not apply to medical exposures is the numerical value of the dose limits for individuals exposed to radiation as patients, on the grounds that the individual benefit from the radiation exposure should greatly outweigh the individual harm, whatever the level of dose, and that some procedures require high doses. At the extreme there is radiation therapy, which involves deliberately giving lethal doses to malignant tissues.

It has been less clear that the system applied to natural radiation but ICRP have settled the matter in a recent publication directed specifically at the control of exposure to natural radiation (ICRP 1984), although here again the numerical values of the dose limits do not apply.

This system has been accepted world-wide as the basis for control of exposure to radiation. This is the main reason that those in the broad business of radiation protection against all sources wish to suggest to those in the narrower business of control of radioactive wastes that it is not necessary to redevelop a protection philosophy from the beginning. The secondary reason is that radioactive waste disposal has international aspects that cannot be avoided, so that if the ICRP system were not adopted, another system would have to be invented and then brought to a similar level of international consensus, starting from scratch. Although this is a secondary reason, it could be of even greater practical significance.

Of the three basic principles the first, referred to as 'justification', deals with the introduction of practices. The practice could be the generation of electricity by nuclear fission or possibly the introduction of a 'new' type of reactor such as a pressurized water reactor. Although waste management implications may have an affect on such decisions it will probably be minor. In any case the decision to introduce the practice was taken decades ago and the problem today is to deal with the wastes that exist now or will soon exist from the operation of the current generations of reactors and reprocessing plant.

The second principle, which I shall abbreviate to 'ALARA' ('as low as reasonably achievable'), follows directly from the assumptions of linearity and no threshold for stochastic effects of radiation. It started off as recognition that a balance had to be achieved between the effort and cost put into radiation dose reduction and the result in terms of reduced radiation-induced harm. It is in essence a restatement of the 'law of diminishing returns'. The underlying common sense of the ALARA criterion has been obscured in recent years by the overemphasis on a particular technique suggested by ICRP for assessing this balance under some circumstance, the technique of cost–benefit analysis (ICRP 1977, 1983). Although this is a useful technique for quantifying some of the inputs to ALARA judgements, it is not very good at quantifying other inputs and tends to constrain the whole process if it is adhered to slavishly. Much of the thinking in radiation protection is now aimed towards clarifying the appropriate role for cost–benefit analysis within the broader decision aiding techniques likely to be useful in systematizing the application of the ALARA idea.

It is worth while to dispel one common misunderstanding about the basis for ALARA being the assumption of linearity between dose and effect down to extremely small doses. Protection is never in reality concerned with radiation doses approaching zero but with increments of radiation dose over the pre-existing and unavoidable dose from natural background. This is of the order of 1–2 mSv a^{-1}, so that doses of concern in protection are usually in a fairly narrow range, over which the assumption that the response curve can be approximated by a straight line is very good. It is true that the slope may not be the same as would be obtained from a linear interpolation between the region of observations and zero, but this is a second-order problem.

Returning to the principles, the dose limits that define, for workers, a region of unacceptability, or conversely a region of potential acceptability, are based on a comparison made by the ICRP with levels of risk of death in industries recognized as having high standards of safety. The dose limits for the public are based to some extent on a comparison with those for workers and to some extent on a judgement by ICRP concerning the attitude of the public to risks of death of the order of 10^{-5} per year.

It is important to recognize that the ICRP recommends a *system* of dose limitation. Remove one element and the system fails. ALARA is only a proper procedure because there is a limit to provide for a not unacceptable level of risk to the most exposed individual. The dose limits are only supportable if accompanied by a rigorous ALARA programme to ensure that most doses are well below the limits.

5. The control system for waste disposal

The ICRP system of dose limitation can be, and is, applied directly to many aspects of waste management and disposal. These include the control of effluent discharges, the regulation of occupational exposures to workers involved in waste conditioning, and the transport of radioactive wastes.

The particular aspects of solid waste disposal that have caused some difficulties in applying the system have been the very long timescales of concern and the potential for disruptive events that, if they were to occur, could give high doses.

These aspects have been discussed *in extenso* over the last five years, both nationally and internationally. The difficulty over the potentially disruptive events has been partly accommodated by recognizing explicitly that the underlying basis for the dose limits was a judgement on acceptable risk and that limitation of dose is only a limitation on probability of harm, and reverting where necessary to a form of limit based directly on limitation of risk. Risk in this context is defined as:

$$\text{risk} = \begin{pmatrix}\text{probability that a dose}\\ \text{will be received}\end{pmatrix} \times \begin{pmatrix}\text{probability that the dose will give}\\ \text{rise to a serious health effect}\end{pmatrix}$$

The first international publication embodying this idea was by the International Atomic Energy Agency (IAEA 1983). This was followed by an Expert Group report from the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (NEA 1984) and was followed early in 1986 by the report of an ICRP Task Group that has been working on the problem since 1982.

In the U.K., the Board recognized that there was a need for criteria to be set for waste disposal that accommodated probabilistic events, and therefore published in 1983 a 'Guidance on Standards' document that attempted to make recommendations that would, if adopted, be reasonably well in line with the way international recommendations were likely to develop (NRPB 1983). By direct analogy with the ICRP dose limits and taking into account both fatal cancers and serious genetic effects, the Board recommended the following limits:

(*a*) the risk to an individual from waste disposal should not exceed 10^{-4} per year;

(*b*) for those situations where doses would be incurred over periods exceeding 10 years, the risk to an individual should not exceed 2×10^{-5} in a year.

These recommendations, and especially the form of them, are substantially consistent with those suggested by the NEA Expert Group. They differ by a factor of 2 as a result of rounding conventions for the risk factors, but as has been pointed out this is not a substantial difference.

The most recent development is the publication by the U.K. Environment Departments of their principles for solid waste disposal (DoE 1984). These incorporate a simplified criterion corresponding to the long-term objective of the Board and NEA, which is expressed in the following way.

> The risk to any member of the public in any one year, from exposure to radiation from all sources other than background and medical exposure, should not be greater than that associated with a dose of 1 mSv.

This corresponds approximately to a risk limit of 10^{-5} per year. The design target for a single repository has been taken as one tenth of that limit. All of these risk limits apply whenever the maximum risk occurs.

It is somewhat more difficult to translate the ALARA component of the system into risk terms but the suggestions being made in the recommendations are that the broad idea of ALARA should be applied to waste disposal decisions and that some of the relevant considerations entering into the decision are the probability and magnitude of the consequences of disruptive events at the repository. Inclusion of these factors is likely to be carried out more easily by using some form of multiattribute analysis system to structure the ALARA decision than by using cost–benefit analysis on its own.

The problem of the very long timescales is being circumvented by recognizing that the ALARA procedure is concerned with choice between available options. In many cases the differences between options will primarily be the effect on dose rates and probabilities of disruptive events in the short to medium term, with the eventual dispersion of radionuclides in the environment being much the same. In this situation the effects in the far future cancel out of the comparison and it is only helpful to the decision to compare the short-term to medium-term effects. Furthermore the uncertainties in the estimates of what will happen to a repository will increase with time; in Europe this will be particularly true during and after the next ice age. If the uncertainties associated with the long-term implications of the options being compared are such that they cannot be distinguished then that aspect is not helpful to the decision and should be ignored.

The decreased reliance on cost–benefit analysis and the complexity of the inputs of ALARA decisions are tending to make the more economic-based techniques, such as discounting of the cost of future radiation-induced effects, less useful than the more decision-oriented criteria just described.

6. Application of the control system

The procedure, then, is to select the available options for treatment and disposal of a particular waste stream, carry out a radiological assessment for each one, as will be described by Hill (this symposium), to determine the maximum individual dose from the 'normal evolution' of the repository, together with the maximum individual risk from 'altered evolutions', both as a function of time, and compare the results with the appropriate limit. This may lead to rejection of some options. If not then the relation to the limit can be considered, with all the other radiological factors including the distribution of collective dose as a function of individual dose level and time, the probability and magnitude of disruptive events, the cost, and – important but difficult – the judgements on the trade-offs between them.

This should give some guidance on the appropriate choice from a radiological point of view, and the sensitivity to the factors involved and the judgements applied. These results are then considered with the other technical and non-technical factors to reach an eventual decision.

7. Acceptance difficulties

This system seems to most of those professionally involved to be reasonably sensible and logically consistent. However, it is clear that acceptance by the public of both the need for waste disposal and the criteria against which to judge repository performance is slow in coming. Here there is a need to take a view that is broader than is usual for a physical scientist to see what the reasons are and whether anything can be done, in a scientific sense, to address them.

The difficulties have been divided into three categories, although even that step may offend some people.

Technical

People have problems with the many assumptions involved in making predictions, especially over the very long timescales used in radiological assessments. These are realistic misgivings (indeed I share them), but in many cases the calculations are necessary and can be justified for the particular purposes for which they are intended. Calculations of maximum risk are intended only to answer the question 'All things being equal, would the future situation arising from the disposal be unacceptable now?' Although it is recognized that all things will not be equal, probably the largest uncertainties in the calculation are whether there will be people there to take the risk and whether cancer induction and hereditary defects will still be a serious medical problem. A substantial defence of this rationale is the lack of even viable suggestions for, let alone agreement on, an alternative.

The difficulties for ALARA comparisons can be dealt with to some extent by explicit recognition and use of the uncertainties, but even this treatment tends to concentrate on sensitivity analysis of technical uncertainties rather than the 'in principle unknowables' that are still subject to assumptions.

As already mentioned, knowledge of the mechanism of induction of radiation effects is incomplete. Although this will improve, it does not seem likely that there will be major changes in estimates, of overall effect, given that the area of concern is incremental doses on background.

Moral and ethical

There is no doubt about the heightened level of public concern over the implications for future generations of radioactive waste disposal. To some extent this concern has been fuelled by the conscientiousness of the radiation protection community in trying to assess these implications and deal with them explicitly rather than ignoring them, as would have happened had radiation protection followed precedent rather than trying to set it. There is now a heightened awareness; there seems to be no option but to wait until it settles into a more balanced view of the overall impacts for the future of all our activities, in their capacity for both harm and benefit.

In part this should be accelerated by relevant comparisons. A large number have been tried, but only a few have so far been accepted as relevant. Some have been poor comparisons, for example that of cigarette smoking: if this is voluntary then it is not regarded as a fair risk comparison; if the comparison is with passive smoking even this is now being regarded as an undesirable and not negligible risk. Other involuntary risks certainly exist at particular levels, such as exposure to carcinogenic chemicals or asbestos, but if brought forward as comparisons may well be challenged themselves rather than regarded as 'accepted'. Probably the technically best comparison is with natural radiation, much of which results from similar radionuclides in similar geological circumstances. However, even in this case people's views of 'man-made' and 'God-given' differ; and, as was pointed out earlier, natural radiation itself is no longer accepted as immutable. Nevertheless, comparisons with natural radiation are valid in the sense that mankind is adapted to living in a radiation environment, so small perturbations of that environment are most unlikely to have disastrous consequences.

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Societal

The discussion of waste disposal is greatly complicated for a mere physicist because it takes place against a background of pressure for change in overall societal objectives by some groups. Waste disposal had been recognized as a possible Achilles' heel of the nuclear power industry, which is itself a vulnerable representative of big, technical, governmental institutions, with overtones of nuclear weapons and military involvement.

These aspects are not really very concerned with doses and levels of risk, so it is not evident that anything can be 'done' other than to ensure that the scientific basis for decisions is rigorous and can be relied upon. The real questions here are political, so that waste disposal, even the nuclear power industry, is only a convenient target.

8. Conclusions

There is now a good consensus on the criteria that waste disposal facilities will have to meet to be declared acceptable by international standards. These criteria are compatible with those used in all other areas of radiation protection. Techniques are being developed to carry out the assessment of potential disposal options for comparison with the criteria and the uncertainties in both the databases and the calculations are better understood and being reduced to manageable proportions. It is necessary to pursue the scientific analysis of waste disposal and its radiological consequences so that these results can be used as a firm foundation to confront, openly and honestly, the concerns of the public and of the politicians.

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Discussion

T. A. Kletz (*Department of Chemical Engineering, University of Technology, Loughborough, U.K.*). The internationally agreed maximum radiation dose for employees (50 mSv or 5 rem) is equivalent to a risk of death of 5×10^{-4} per year or about 10 times the average risk of death of employees in manufacturing industry in the U.K. This seems rather high. Of course, very few employees are exposed to the maximum permitted dose and the average dose is much lower but if I am exposed to the maximum dose it is not much consolation to be told that the average risk to me and my workmates is low.

Although smoking is a voluntary rather than an imposed risk, it may nevertheless be useful to point out that a risk to the public from radiation of 10^{-6} per year (say) may be counterbalanced by smoking just one cigarette less per year. If that is all the risk that radiation produces it seems hardly worthwhile getting worked up about it.

The nuclear industry spends tens or hundreds of millions of pounds to save a life. Doctors can save lives for tens of thousands of pounds and road engineers for hundreds of thousands of pounds so the nation gets poor value for money from the nuclear safety people. Lives would be saved if we gave them less money and gave the doctors more.

G. A. M. Webb. The risk comparison used by ICRP in Publication no. 26 was between the average level of risk from occupational exposure to radiation and in other occupations recognized as having high standards of safety, which are generally considered to be those in which the average annual risk of death is about 10^{-4}. The limit, being that above which you must not go, is clearly higher than the average. Continuous exposure of the same person over a working lifetime at or close to the limit results in a risk that is higher than this average for other 'safe' industries.

I recognize the factual accuracy of the comparison with cigarette smoking but I feel the other dimensions of the risks stop the comparison from being very useful.

In the longer term I believe we should be endeavouring to allocate health protection resources where they will give the greatest benefit. The forces causing the nuclear industry to 'overspend' and the medical profession arguably to 'underspend' are not primarily related to the economics of health protection but are, as I have indicated in my paper, rather broader.

S. H. U. Bowie, F.R.S. (*Tanyard Farm, Clapton, Crewkerne, Somerset, U.K.*). Is there any evidence to show that exposures to levels of radiation that occur naturally have any deleterious effect on the health of animals or man? Is the threshold to which Dr Webb referred lower or higher than the upper limits of radiation known to occur in association with uraniferous rocks in many parts of the Earth's crust?

G. A. M. Webb. I am not aware of any direct evidence of harm to members of the public from exposure to natural levels of radiation. However, the levels, risk estimates and difficulties of epidemiology are such that we would not expect to see this direct evidence. Absence of proof of harm does not imply proof of absence of harm. There is, however, a fairly short extrapolation from observed cancer induction in workers exposed to natural radionuclides in underground mines to deduced risk to people in homes from the same radionuclides.

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