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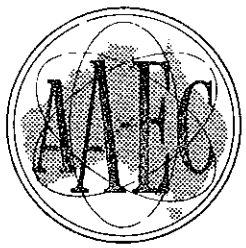

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ENVIRONMENTAL HAZARDS OF FOSSIL AND NUCLEAR POWER PRODUCTION

by

G.M. WATSON

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# ENVIRONMENTAL HAZARDS OF FOSSIL AND NUCLEAR POWER PRODUCTION

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## ABSTRACT

It is now essential for engineers to recognise the environmental hazards which may be associated with their constructions and to make proper allowance for them when costing different solutions to a problem. Both nuclear and fossil-fuelled power stations present environmental hazards, and these can be traced from mines through processing plants to power station wastes. It is necessary that engineers develop an appropriate basis of comparison if they are to assess the relative environmental costs of nuclear and fossil-fuelled power stations; this must allow for effects on health, ecological effects and aesthetic effects.

The biological effects of radiation have been fairly well quantified with respect to major exposures, but there is still uncertainty on the precise form of dose-response relationships at low doses, such as might be relevant to industrial and public health. There are also uncertainties for non-radioactive pollutants, and it is probably not very logical to treat the dose-effect relationships of radioactive and chemical pollutants as being quite different in nature, as is commonly done at present.

continued

ABSTRACT (Continued)

There are internationally accepted standards for allowable radiation exposure. It is possible to base allowable discharges of radioactive contaminants to the environment on these standards, provided the modes of dispersion are understood and possible pathways to the exposure of man are recognised.

The philosophy of radiation protection recognises that although radiation risks can be made very small, they cannot be abolished entirely, and that these risks must be balanced against the benefits of using radiation. These risks can be quantified and compared with other hazards of work and life which people accept, voluntarily or involuntarily.

There are insufficient data available on the effects on health of various pollutants, and there is too little public agreement on the relative worth of mined and unmined natural resources, to allow a detailed comparison of the environmental hazards of nuclear and fossil-fuelled power stations, but it is possible to begin this comparison in limited areas.

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ACCIDENTS; AIR POLLUTION; BACKGROUND RADIATION; CONTAMINATION; COST; DELAYED RADIATION EFFECTS; DOSE-RESPONSE RELATIONSHIPS; EARLY RADIATION EFFECTS; ECOSYSTEMS; ENVIRONMENT; ENVIRONMENTAL ENGINEERING; FOSSIL FUELS; GENETIC RADIATION EFFECTS; ICRP; NUCLEAR POWER PLANTS; OCCUPATIONAL DISEASES; PERSONNEL; PREVENTIVE MEDICINE; RADIATION DOSES; RADIATION HAZARDS; RADIATION PROTECTION; RADIOACTIVITY; TOXICITY

CONTENTS

## INTRODUCTION

In a simpler age the power utility and power station engineer had only to compare capital construction costs, operating and fuel costs, and the costs of distribution, in deciding what sort of station they would build and where they would put it. In fact, the decisions were largely made for them by the relative availability of coal and oil at the seats of demand. Now they must consider another factor, the environment, and this is one which is much more difficult to incorporate into their analysis of costs. It is difficult because the engineer has no simple yardstick for environmental values, and because a lot of people would disagree with his conclusions even if he did. In no advanced country, at least, can he disregard the overall environmental effects of his construction, whether these are expressed in health hazards to man, in changes to the natural environment of the plant, or even in the aesthetics of the site works. He cannot even dodge the issue by constructing a hydro-electric power station where this is feasible; that course may land him in just as much trouble.

For the purpose of this discussion, environmental hazards will be taken to include effects on human health, on the living things of the environment, and on the inanimate environment - the air, waters, soils and rocks which support life and possess varying degrees of intrinsic appeal to man. In this sense, environmental hazards are not confined to the environs of the power station; if we are to compare the environmental costs of different sources of power, the comparison must start with the mines which produce the fuel and extend through any fuel processing plants which may be necessary to the power station itself. In matters of health we are concerned for the miners, the workers in the various kinds of plant, and the people who may be affected by wastes from either mine or plant. Therefore in assessing the environmental costs of power production, the engineer has to consider, and attach an appropriate value to, factors other than the mundane problems of his direct costs. These are relatively new tasks for him and he may find it difficult to give the right weighting to what may seem purely aesthetic considerations, or to evaluate the relative costs to health of different sources of power. These factors are less amenable to economic analysis than the fuel and construction costs which he has always had to consider.

These matters are not merely awkward questions for the engineer; if his decisions are reached in a rational manner and with public interest paramount, they should be acceptable to the community. In this country, as in most others in recent years, many people have been reluctant to accept the engineers' judgement in matters involving the environment. For good or bad reasons they mistrust his judgement and would prefer to substitute their own. It is quite legitimate to question such decisions as the location and type of power stations but, if the critic is to be taken seriously, it is incumbent upon him to become properly informed on the matters he disputes. If he does not, the disagreement is likely to degenerate to unproductive argument or emotionalism, and necessary decisions may be delayed. That situation appears to have been reached in some American hearings on the location of nuclear power stations. We should try to avoid following that example and, to do that, we have to provide the engineer with the yardstick for environmental values that has been mentioned already. Moreover, this yardstick must be acceptable to informed critics; rational discussion demands that people speak the same language and are able to respect each other's opinions.

The notice of this Symposium expresses the hope that the 'discussion of these (and other) topics will lead to a consensus and perspective for the immediate future'. Therefore I think it appropriate that we should attempt here to define the problems at issue in this topic and look for ways to resolve them. My discussion will begin from the standpoint that we have a rapidly growing demand for electric power and seek the best way of meeting it. It will not question whether we really need the rates of growth that are commonly forecast for power production, though that is a point on which some people would disagree. The engineer will see his problem primarily as one of optimising his costs, therefore it will be easier for him if we attempt to calibrate the hypothetical yardstick for environmental values in dollars rather than measures of health or of aesthetic value. This is logical because it will cost the engineer a specific sum to meet particular health standards or to take the countermeasures prescribed for avoiding some ecological or other environmental outrage. Whether these costs are matched by equivalent benefits is less easy to determine. Morbidity and mortality of man do not really constitute a problem - the compensation courts adjudicate daily on man's value alive or dead - but attaching a dollar sign to alternative uses of land or to the loss of some natural feature is a less

exact science, and one subject to much emotional bias. However, if a conservationist disputes (say) the right of a miner to dig holes in a national park, he should be prepared to argue his case in value terms and to show that his solution to the problem is of more lasting value to the community than the miner's. There is nothing inherently impossible in this. In settling claims for damages after accidents, courts allow for loss of the ability to enjoy various aspects of life; all the conservationist has to do is extend this principle to cover a population in space and time.

The decision to make use of a particular uranium or fossil fuel deposit as source of power would ideally be made as part of an integrated overall plan for the optimum use of the country's resources. Such a plan would extend into the future as far as can reasonably be foreseen, and it would recognise and make allowance for the accompanying environmental effects. It would recognise that human well-being would sometimes be better served by leaving a particular deposit in the ground rather than by taking it out. The engineer's final analysis should also consider that there may be other useful things to do with fossil fuels besides burning them; that is not really part of the brief for this paper but it has some relevance in that coal and oil bodies are likely to be extracted, and hence cause environmental damage, whether or not they are used in power stations.

## SCOPE OF THE ENVIRONMENTAL PROBLEM

Comprehensive analysis of the problem requires that we should consider all phases of power production in relation to the health of man, the well-being of other living things, the aesthetics and the prospective uses of the land in question and, not least, what will be the consensus of public opinion on particular projects. We are not now in a position to deal with all these things, or even any of them, comprehensively and quantitatively. In spite of this, I think it is worthwhile to set out in tabular form a checklist of headings that should be considered in a comparative environmental assessment of power production. Each heading would need breaking down into fine detail for any real example. Table 1 gives such a list. It may well be incomplete, some of the inclusions debatable, and some much less important than others but it will help to identify what has to be done and what are the fields in which we are particularly ignorant. All evaluations indicated by the list need to be carried out both for normal operating conditions and for accident conditions using the best available estimates of probability for the latter.

In the ideal situation, the engineer confronted with a demand for, say, 1000 MW of electrical power, would assess the environmental costs of providing it, in terms of some such framework as that indicated in Table 1, add the figures to his estimates for the other components of the total cost, and come to a rational decision on what type to install. He might even hope that most people would agree with him. In real life he will not have all the information he would like before making his decision. He then has to compromise, and his decision is likely to offend some-one. It is important that agencies which may have to endorse his decision treat the compromise objectively and do not criticise it for being less than perfect in some respect. In no field of human activity is it possible to guarantee complete freedom from risk. Power generation is no exception; all kinds are accompanied by finite risks to man and his environment.

TABLE 1 ENVIRONMENTAL HAZARDS OF POWER PRODUCTION

| PROCESS | Type of Hazard | Nuclear | Coal | Oil |
|---|---|---|---|---|
| Mining | Industrial Health | + | + | + |
| | Public Health | + | | |
| | Ecological Damage | + | + | + |
| | Inorganic Damage | + | + | + |
| Extraction, Refining, Cleaning, Storage, Transport | Industrial Health | + | | + |
| | Public Health | + | | + |
| | Ecological Damage | + | + | + |
| | Inorganic Damage | + | + | + |
| Fuel Manufacture, Fuel Reprocessing | Industrial Health | + | | |
| | Public Health | + | | |
| | Ecological Damage | + | | |
| | Inorganic Damage | + | | |
| Power Plant | Industrial Health | + | + | + |
| | Public Health | + | + | + |
| | Ecological Damage | + | + | + |
| | Inorganic Damage | + | + | + |

Notes

+ denotes an area of potential interest.

Inorganic damage refers to changes in the inanimate environment.

Industrial Health refers to plant workers, Public Health to the general public.

## BIOLOGICAL EFFECTS OF RADIATION

The potential hazards of radiation are prominent in people's minds. This may arise from the intangible nature of ionizing radiation, from fear or guilt over the use of nuclear weapons, the physical indestructibility of radioisotopes, or because the consequences of exposure may be visited on later generations. The fears are irrational, the biological effects of radiation do not differ essentially from those of other agents. There is a continually expanding list of purely chemical agents which, applied to individuals or loose in the environment, can produce the same unpleasant consequences of cancer or genetic damage as does radiation. Other agents are used to kill cells acutely, just as the radiotherapist uses radiation. What is different about radiation hazards is that they have been studied more exhaustively than any other, and we are in a better position to predict their magnitude. Since, in chemical terms, biological material is immensely complex, and its structure is equally complex, we are a long way from being able to identify precisely all the effects that radiation has on cells. Nevertheless we can give a fairly precise description of the ultimate effects on whole organisms. These can be categorized as acute or short-term effects, delayed somatic effects, and genetic effects.

### Short-term effects

By this is meant consequences which appear at intervals after a radiation exposure varying from minutes to a few weeks depending on dose and dose rate. At the cellular level they usually mean cell death, the effect which radiotherapists use in treating cancer; at the whole-body level they vary from trifling illness to death. Accidents producing such consequences are so infrequent that we need not consider them further here.

### Delayed somatic effects

These are effects which appear months or years after exposure and are of several kinds. Two, of relatively minor importance, are cataract, which can be a sequel of moderate exposures, and premature aging which can be demonstrated in laboratory animals after whole-body exposure but is of doubtful significance in man exposed at occupational levels.

The most important delayed somatic effect is the induction of malignant disease. By 'somatic' is meant an effect on cells other than germ cells. Cancers of various kinds are readily produced in experimental animals by single large or repeated smaller doses of radiation, but since the genetically pure strains of mice generally used in these experiments vary greatly in

their responsiveness and the type of cancer or leukaemia induced, it is not possible to use them as a model for direct extrapolation to man. However, there is no reason to doubt that radiation exposure can induce most or all types of human cancer. What, unfortunately, is in doubt is the precise form of the dose-response relationship at low doses or at low dose rates. We have fairly good evidence on the incidence of leukaemia, the most likely consequence of whole-body over-exposure, at doses of 100 rads and above given quickly, but only meagre evidence for low doses and dose rates. This is of course precisely where we most want information for setting occupational and environmental limits. It does not mean we cannot set them, but it does mean that they are probably set at more conservative levels than really necessary.

Genetic effects

The effects of induced mutations are not seen in the recipient of radiation exposure but in his offspring or in subsequent generations. As with the induction of cancer we have built up a fairly extensive knowledge of the dose-response relationship for laboratory species, but we cannot extrapolate directly to man. There are undoubtedly some dose-rate effects in the radiation induction of mutations in mammals - that is very low dose-rates of the kinds we are interested in are considerably less effective in inducing mutations than high dose rates - but this has not been taken into account in setting limits, and these are probably lower than they need be. It is of course very difficult to conduct satisfactory animal experiments on low-level radiation mutagenesis or carcinogenesis, because the number of animals needed for significant results becomes astronomic.

Implications for radiation protection

The appropriate advisory bodies of most countries, including Australia, recommend that legislators endorse (except in minor detail), the Recommendations of the International Commission on Radiological Protection (ICRP) with respect to radiation exposure limits for those occupationally at risk and for members of the public. Limits of concentrations of radioisotopes in environmental materials can be derived from the dose limits for the public. The ICRP makes the conservative assumption that any exposure to radiation, however small the dose or low the dose-rate, carries some risk for the development of malignant disease or of genetic effects. That is, there is no wholly safe dose of radiation and the policy of assuming some risk is the most reasonable basis for radiation protection. In the face of the uncertainty of the form of the dose-response relationship at low doses, the ICRP assumes that effect is proportional to dose, right down to the

lowest levels and irrespective of dose rate. The ICRP notes that this approach may lead to a gross overestimate of the incidence of effects from chronic low-level exposure, some of which may not occur at all, but regards it as the only approach which can reasonably be adopted in our present state of knowledge. It is implicit in this thinking that some level of risk is an acceptable one in relation to the benefits which derive from the activities producing it.

## RADIATION VERSUS CHEMICAL TOXICITY

If we are to compare the environmental effects of radioactive pollutants with those of others, we need some objective basis for the comparison. It was indicated in the previous section that there may be no qualitative differences in the nature of these effects, but what is really at issue is whether or not there is an essential difference in the form of the dose-response relationships. If we knew them precisely for all classes of pollutants, comparisons would be simple.

Most countries have prescribed 'threshold limit values' for various atmospheric contaminants, dusts, fumes and the like, which may affect the health of workers exposed to them. In some cases similar limits for toxic chemical pollutants, including limits for concentrations in foodstuffs or water, have been set down for the public. In contradistinction to radiological health practice, it has usually been assumed that exposure to levels below the limits has no ill effect. This assumption is not necessarily justified.

Figure 1 indicates some different possible dose-response relations. Curve A is a 'threshold' type curve and has the form we associate with chemical or pharmacological toxicity; the end-effect measured is usually death or some defined state of ill-health. Data of this sort led to the setting of 'safe' levels for various industrial pollutants, that is levels below which the unwanted effect is not seen. With progress it often became possible to detect the onset of unwanted responses before overt illness by using as indices various non-specific responses to environmental stimuli. This raises the questions: Is it possible to distinguish between those kinds of response which have significant implications with respect to health and those which do not? If such different categories exist, can the point be defined beyond which the detection of change has no significance as a health hazard? Is there really a threshold below which no harm results, or should we equate any kind of response with potential ill-health? (Hatch, 1971)

Certainly there seems no good basis for treating potential chemical carcinogens and mutagens on a different basis from radiation, but it is not obvious how we should treat agents, for example sulphur dioxide or smoke, which are known to cause morbidity above certain concentrations but may not be accepted as carcinogens.

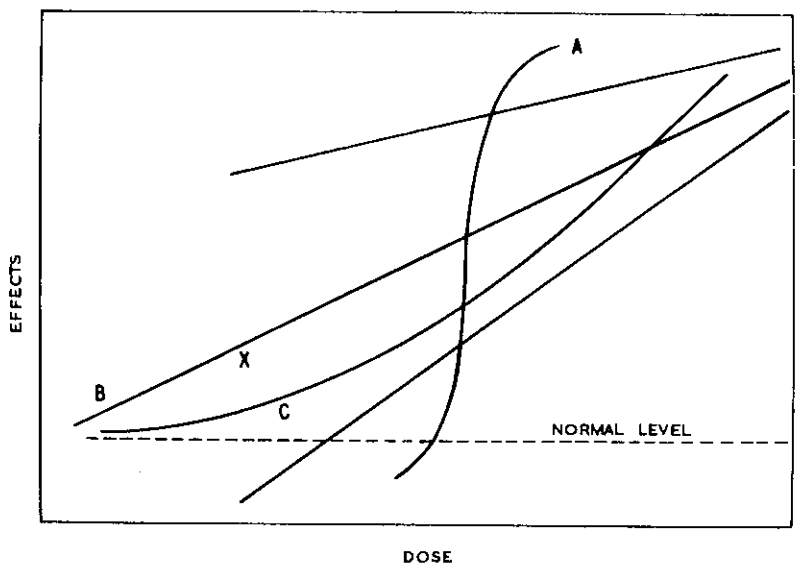


**FIGURE 1 TYPES OF DOSE-EFFECT RESPONSE**

If radiation response is measured in terms of acute illness or death, the dose-response curve is also of the threshold type A in Figure 1. If the response measured is the incidence of malignant disease or of mutations, the ICRP assumption is that the linear curve B applies. Now, as the dose is reduced the experimental uncertainty of points on such curves increases, and I have illustrated this (in a quite arbitrary way) by putting in two other lines to show the margin of uncertainty. At doses below the point X there are no data and, in real experiments, the value of X can be high in relation to environmental standards. Clearly, the uncertainty of the available data means that they could just as well be fitted to some other curve, perhaps a second power response as curve C. In that case there would be the appearance of a threshold, since at low doses the effect would be indistinguishable from natural levels which are not zero. Figure 2 shows some data from an actual experiment (Finkel et al, 1958). The authors suggested, not unreasonably, that their data fitted a threshold hypothesis for the induction of bone tumours by strontium-90 injected into mice. Subsequently they were admonished by critics for not putting their conclusions rather differently - that there was no evidence of a threshold and that the results were consistent with a linear hypothesis. In fact, these figures and others can be reconciled with either view. This raises a question we should keep in mind when thinking about effects at very low doses. Is an effect real if we have no means of detecting it?

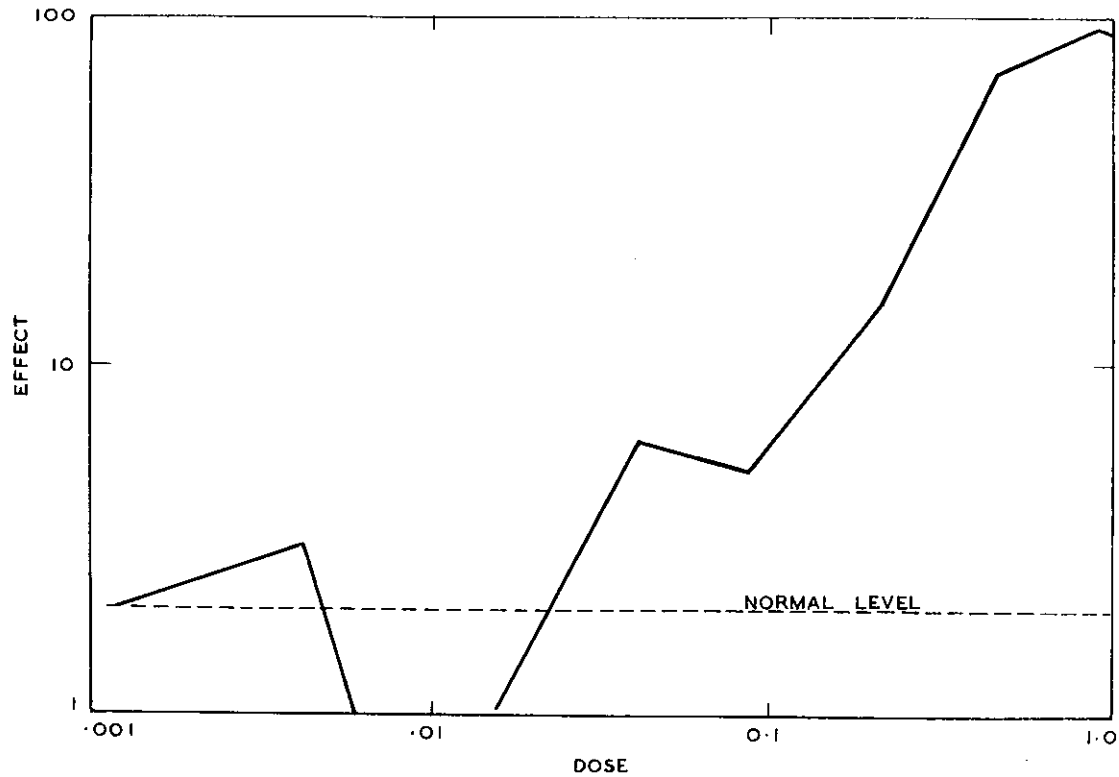


FIGURE 2 INDUCTION OF BONE SARCOMA BY STRONTIUM-90

The purpose of this section has been to suggest that we should not necessarily treat the dose-effect relationships of radiation and chemical pollutants as being quite different in nature. In our present state of uncertainty it would seem more rational to compare radioactive and other pollutants by assuming they have similar dose-response relationships, so in order to be consistent and conservative, I suggest both be treated on a linear non-threshold basis. Definition of the dose-response relationship in this way allows us to calculate the expected yield of some effect, e.g. the incidence of tumours, as a function of radiation dose. In time we may be able to show that the function is not always linear.

ENVIRONMENTAL ROUTES OF RADIATION EXPOSURE

There are two problems to be identified here; protection of the environment as such, and the protection of the people in that environment. This section will deal primarily with the second of these, the protection of man, since for him there are acceptable limits of radiological exposure from which we can logically derive operational limits for the release of radioactive materials from mines or nuclear plant. Mines, especially, are apt also to produce chemical pollutants. It is probably legitimate to treat the risks to man from metallic or other chemical pollutants in the same general way as radioactivity, though there are generally fewer data available.

Background radiation

The effects of man-made or man-released radiation should be assessed within the perspective afforded by the existence of a ubiquitous background of natural radiation. This arises from cosmic radiation which is altitude and latitude dependent, from terrestrial gamma radiation which varies with soil or rock type, and from naturally radioactive constituents of the body, in particular potassium-40. The total average background radiation to which an individual is subject is in the region of 110 millirem per year but in many centres it can be twice this figure, and much more in a few parts of the world, without any ill effects being evidenced. So it is not unreasonable to regard exposures of 100 millirem or so per year, in addition, to the normal background, as being trivial. It might also be appropriate to mention the 'medical' background. In the U.S.A., the latest estimate of the average genetically significant dose per year from medical X-rays is 95 millirem, with a whole-body equivalent of about twice that. Although the ICRP excludes medical exposure from its recommendations it is clear that it needs to be kept in mind when considering the allocation of quotas of man-made radiation exposure to a population.

Criteria for the release of radioactivity

The last paragraph indicated that some degree of radiation exposure to man can be regarded as trivial. It is implicit in our thinking that some larger amount is too much, and it is necessary to decide what is a proper upper limit for individuals, occupationally exposed, or as members of the public without control over their exposure. This question can be extended to ask what is the proper upper limit for the mean exposure of a population; should it perhaps be less than that derived from the sum of the allowed individual doses. These questions have engendered a good deal of acrimonious controversy, but governments of all political hues and their specialist advisers have generally gone along with the recommendations of the ICRP for both occupational and involuntary exposure. For environmental purposes the relevant recommendation is that the dose limit for the gonads, bone marrow and whole body, for a member of the public shall be 500 mrem in a year. In this country this is spelt out with varying degrees of clarity in State regulations, and explicitly in a publication of the National Health and Medical Research Council. It is possible to place additional limitations on the neighbourhood dose from particular nuclear facilities, or to set an overall population limit for the dose from nuclear wastes, and both these measures have been used in other countries to minimize exposure. From whatever figures are

accepted as dose limits it is possible to derive limits for the release of radioactivity to the environment which will ensure that individuals or populations do not exceed their allowed quota of radiation exposure.

Calculation of allowable releases

In nuclear operations of all kinds, mining and milling, fuel fabrication and reprocessing, power production, it is not practicable to confine radiation and radioactivity absolutely. There will usually be many and complex pathways by which released radionuclides will ultimately cause some radiation exposure to man. In the ideal situation it would be possible to make a complete inventory of the distribution and fate of released radionuclides; in practice this is not necessary since in any given situation it will be possible to identify certain nuclides and pathways as being more important than others. These are then designated as the 'critical' nuclides and pathways, since they will determine the limitations on discharges to the environment. Within these pathways will exist one or two groups of people whose characteristics or habits in some respect, age, location, eating habits for example will cause them to receive greater doses than the rest of the population, and these groups may also be designated 'critical'. Their behaviour will provide the limits of discharge. In preliminary planning, or where the expected doses to the critical group are clearly very small, it may be sufficient to postulate a hypothetical group with extreme characteristics, e.g. drinking undiluted effluent. The estimated dose to such a group will exceed that which could be received by any real group of people. In any real situation it will usually be wise to adopt a pragmatic approach as well as the analytical one. That is, after releases, set conservatively, have begun, appropriate components of the environment will be sampled and a factual basis supplied where possible for the analysis.

The pathways by which released materials can find their way to man can be complex. For example, the radioisotopes of iodine and strontium may be released to the atmosphere, be deposited on grass, the grass eaten by cows, and the radioisotopes finally ingested in milk by children. Marine dispersion may be still more complicated. Released radioactive metals may be taken up in succession by phytoplankton, zooplankton, molluscs and crustaceans, small fish, larger carnivorous fish, and finally man. At each stage there may be a concentration factor, and in some instances these are very high. For example, oysters will concentrate zinc from seawater by a factor of $10^4$ or more, and for this reason oysters grown near the outfall of nuclear power stations are likely to contain traces of zinc-65.

The ICRP does not define limits of radioactivity for the various foodstuffs that enter into these calculations. It does provide tables of the maximum concentrations allowable in drinking water for persons occupationally exposed. These concentrations would give the 'standard man' who drinks 2.2 $\ell$ of water daily, a body burden of the nuclide in question just sufficient, at equilibrium, to irradiate the most sensitive organ to the allowable limit. Dividing the listed concentration by 30 gives the figure appropriate to the general public. Since the concentrations are given as $\mu Ci/cm^3$, multiplication by 2,200 gives the allowable daily intake for each radionuclide. From this derived limit it is possible, if the pathway, eating habits, concentration factors and dilution factors are well-enough known, to quantify allowable releases for each radionuclide. Since the effects of ingested radionuclides are additive, any discharge authorization must allow for their summation in the calculations. Similar arguments can be applied to atmospheric dispersion.

Environmental control

Pre-operational investigations have several objectives:

(a) To obtain sufficient information on what are the critical radionuclides, pathways and population groups, to allow at least a provisional evaluation of what discharges are allowable. In some cases it may be better to postulate a hypothetical critical group with extreme characteristics, which will be the 'worst case', as a basis for initial formulation. Observation will then allow refinement.

(b) To provide information on pre-operational levels of radiation and radioactivity. These will not affect the conduct of operations but will facilitate the interpretation of later results.

(c) The conduct of experiments to obtain unknowns, e.g. concentration and dilution factors and, for chemical contaminants, allowable concentrations for local habitats.

Post-operation environmental surveys are necessary to:

(a) Provide evidence that the assumptions underlying discharge formulations are valid or conservative.

(b) Provide sufficient random sampling to ensure that unrecognized pathways of exposure do not exist.

(c) Provide the data necessary to meet the needs of good public relations.

The work required under the first two headings is self-limiting and, providing there are no major changes in plant operation, should reduce with time. It is important to review the monitoring programme from time to time, not only because it might have been wrong in the first place but because review when operations are stabilized may allow substantial reductions in the scale of monitoring programmes. In installations where processes and waste releases are closely monitored, environmental monitoring may become unnecessary.

In summary, the philosophy of radiological environmental control is to restrict exposure of the public to ICRP-originating limits for individual members of the public. The ICRP also provides for a limitation on genetic dose to the population (not dealt with by the N.H. and M.R.C.) but this is unlikely to have relevance, in the present context, for many years if at all. It is also a sine qua non that doses are kept as low as possible, but the definition of 'possible' is rather subjective.

## ECOLOGICAL RADIATION HAZARDS

In the early period of nuclear development the folklore of nuclear establishments included stories of such things as two-headed frogs and other obscure monsters being found in the surrounding ditches and streams. These reports sometimes appeared in the lay press as a manifestation of the potency of radiation as a mutating agent. We need not take these stories seriously but it is proper to ask what may be the radiological effects of a nuclear power plant, or other nuclear facility, on the various plant and animal species in its environment.

The answer is simple; it is most unlikely that there will be any detectable effect. Large scale site works - the construction of buildings, roads, cooling ponds etc., - will of course produce ecological changes, but these are common to all types of power station, and the only possible difference in a nuclear station is a marginal increase in thermal waste. Purely radiological effects will be governed by the restrictions introduced to protect man. In general, man is the most sensitive species at risk, is at the end of the foodchain and therefore most affected by concentration factors, and is the longest lived of the species in the sequence. In round terms, effective exposure is related to the product of these three factors; therefore, if man is protected, the other species are better off. There are factors which act the other way, for example the protracted residence of zinc in molluscs, but it can still be shown that, if consumption by man is allowable, the exposure of the mollusc is trivial. There is the further point that the offspring of man mostly survive, and their absence would be noted, whereas in the lower orders it is commonly believed that numbers will be limited by the availability

of food and by predators, and a few losses from radiation would not be noticed.

ACCEPTABLE RISKS

The ICRP emphasizes the need to balance the risks of radiation against the benefits which come from its use. It remarks that, unless man dispenses altogether with activites which involve exposure to radiation, he must recognise that there is a degree of risk, and limit radiation dose to a level which is acceptable to the individual and to society bearing in mind the benefits derived. Since our regulations endorse ICRP recommendations it must be assumed that we agree with the concept of an acceptable dose and with the ICRP setting for the delicate balance between risk and benefit. Of course, there are individuals who disagree, often vociferously. How was this point of balance arrived at, and is this approach illogical in singling out a particular human activity for special treatment? Or should we extend it and enquire whether other sorts of activity are worth the risks they entail? If we are to make meaningful comparisons between the hazards of nuclear and fossil-fuelled power stations, it will be necessary to consider the risks in both cases, and we shall have to extend the ICRP concept of risk, which is centered on mortality, to include morbidity. These steps are pre-requisites to the cost analysis of environmental hazards which was proposed earlier.

It may help us to think about these questions if we are aware of the magnitude of everyday risks, and of the difference in magnitude between risks voluntarily accepted, e.g. riding a motor cycle, and involuntarily accepted risks, e.g. public utility vehicles. Most people know that it is safer to go somewhere by aeroplane than by car, but may not know that the lifetime occupational risk of death for aircraft crew is rather worse than for a coal miner, whose risk in turn is worse than for industry in general. The figures given here come mostly from two papers by Sowby (1965, 1971) and one by Starr (1971), and have been rounded off in some instances. The overall risk of dying in Western countries is about 1000 per hour per $10^9$ persons.

TABLE 2

Accident death rates for some occupations

(death rate per hour per $10^9$ persons).

| | |
|---|---|
| Steeple-chase jockeys | 500,000 |
| Professional boxers | 70,000 |
| Air crew | 2,500 |
| Construction workers | 675 |
| Railway shunters etc. | 450 |
| Coal Miners | 400 |
| Fishermen | 300 |
| All Males | 100 |
| Doctors | 60 |
| Printers | 35 |

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Evidently interest, money, or the inability to find some other job leads some of us to much more hazardous occupations than others. Of course, the hourly rate does not tell the full story. Miners spend much more time in the mine than aircrew spend flying, and this removes a lot of the difference when integrated over a lifetime. Table 3 shows a few lifetime occupational risks.

TABLE 3

Lifetime occupational risks as percentages

| | |
|---|---|
| Aircrews | 7 |
| Construction | 5 |
| Fishing | 5 |
| Coal mining | 2 - 5 |
| Pottery | 2 |
| All industries | 1 |
| All manufacturing | 0.5 |

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Table 3 does not allow for non-fatal illness which may be significant for coal miners and pottery workers, who are liable to pneumoconiosis. We might ask: To what extent are people prepared to accept risks? This can be assessed by relating wages to accident risks, and Starr's figures suggest that acceptance of individual risk can be approximated by a third-power relationship. Another point is that risks seem to reach a risk-benefit balance; this is exemplified in the U.S. by motor cars where the fatality rate per hour has become stable. In Australia, one hopes the rate has overshot the balance and is decreasing.

The risks associated with exposure to radiation should be considered in relation to the everyday risks already quoted. Consider first occupational risks for 'radiation' workers who may receive, under the usual regulations, up to 5000 millirem per year during their working lives. Their risks may be estimated from their assumed exposure and the estimate compared with the actual incidence of death or fatal disease. The average radiation worker certainly does not receive 5000 millirem, it is doubtful if he receives a tenth of that, but if we assume he receives 1000 millirem per year, and that the risk coefficients suggested by the ICRP (1966) are valid, his lifetime risk from leukaemia or other cancer comes out at 0.16%. This is low in relation to the specific risks of other occupations. It must be emphasized that the risk data used here are upper limits of an estimate and are extrapolated from observations at high doses. The true risks are likely to be less, possibly much less. There are, of course, conventional risks also, but these are known to be below average for industry as a whole. We may compare this hypothetical risk to a radiation worker with some actual figures from industry. The figures given below come from the U.K. Atomic Energy Authority; the evidence is negative, and therefore perhaps not completely convincing, but it does at least indicate that radiation workers are not appreciably more likely than anyone else to die prematurely or of cancer.

TABLE 4

U.K.A.E.A. STATISTICS FOR MALE STAFF 1962-1969

| Causes of Death | Actual | Expected (actuarial) |
|---|---|---|
| All causes | 1,467 | 1,986 |
| All cancers | 379 | 513 |
| Lung cancers | 150 | 224 |
| Leukaemia | 6 | 13 |

The second question is what are the risks to populations involuntarily exposed to the effluents of nuclear facilities. These risks must be no more than one tenth of occupational risks, on the linear hypothesis, and in practice much less than that because the 500 millirem (0.5 rem) limit applies at the boundary fence of nuclear facilities and the mean population dose must be very much less. It is reasonable to answer this question on the basis of actual experience with the operation of United States light water reactors, currently the most favoured type of nuclear power plant. Operational experience in 1969 with these reactors showed that 8 of 13 plants released less than 0.1%, 3 plants up to 1%, one plant 3.6%, and one plant 31% of the allowed discharge of radioactive gases to the atmosphere. The estimated average dose to the local population from these releases is 0.01 millirem, or $10^{-4}$ of the average natural background. This figure is clearly without significance. Discharges of liquid effluent also did not result in any measurable exposure (Rogers and Gamertsfelder, 1971). Since that date allowable emissions from such reactors have been reduced by a factor of 50-100, and there will evidently be no difficulty in meeting this requirement which applies equally to one or a group of power stations. Radiation exposures of the magnitude implied by the operation of these reactors adds nothing to the daily risks of life.

## FIRST APPROACH TO NUCLEAR-FOSSIL COMPARISONS

Earlier it was suggested that an engineer who was asked to provide electrical power might assess the comparative environmental costs of different solutions to his problem in terms of some such headings as those listed in Table 1. We cannot consider all these things here, nor do we have the data which would allow them to be assessed properly, but it might be useful to consider one particular aspect. This is 'public health' and it is probably this aspect which has most aroused public concern about the building of nuclear power stations. People fear they may become victims of insidiously poisonous effluents from the stations, or that there may be accidents with disastrous consequences for the public.

There are various ways to approach this problem. One is to consider each of the likely possible pollutants separately, e.g. radioactive noble gases and tritium for nuclear reactors, particulates and sulphur dioxide for fossil stations, and compare the effects which might be produced by the output of these materials from stations of comparable size. We could make a reasonable guess at the limiting overall effect of tritium and krypton-85 on a global basis, if we assume complete dispersion and equilibration, but it would be much more difficult to do the same thing for sulphur dioxide and particulates since they do not have a fixed half-

life. Nevertheless that is an approach which should be considered in the future because there are now appearing quite a number of investigations which attempt to define quantitative relationships between ill-health and death, particularly respiratory illness, and smoke or sulphur dioxide levels in a community. At present the extrapolations necessary for this approach are rather doubtful.

Another approach is to look at existing estimates for the health costs of atmospheric pollution from the use of fossil fuel and see to what extent these may be offset by the substitution of nuclear energy. I propose to take some data from various United States sources; I don't think anyone would claim very high accuracy for the figures but they are probably in the right order of magnitude.

One set of figures puts the annual cost of respiratory disease in the U.S. at $4,887 million, and estimates that a 50% abatement in pollution levels would eliminate 25% of respiratory morbidity and mortality. If we assume that 25% of the pollution comes from fossil fuel power stations, their replacement by nuclear plant would reduce the cost of respiratory disease by $305 million even if pollution reduction is only half as effective as claimed. For cardio-vascular disease evidence is less strong, but allowing for this by a further reduction of 50% the saving comes out at $115 million. These health costs were based on 'earnings foregone' and are probably a substantial underestimate of what people are really prepared to pay for health. Any gain in this way from the substitution of nuclear power must be offset by health losses attributable to its use. For this we need a figure for population radiation dose from the use of nuclear power. Calculated mean doses from atmospheric contamination, based on the former U.S. limit of 500 millirem at the boundary fence, are around 0.28 millirem per year; this could be doubled to allow for exposure by other routes. Since actual emissions are mostly less than 1% of what was then allowed, the estimate is probably high by one or two orders of magnitude. But if we put population exposure at a very conservative 1 millirem, take the U.S. population to be 200,000,000 take the ICRP figures for the induction of cancer and leukaemia, and assume the average citizen to be worth $200,000, the debit for the change to nuclear power comes out at $1,600,000. This is of course an upper limit and the true figure may be less.

Studies have also been made on the basis of an individual 1000 MW station. After optimizing pollution control, a fossil fuel station of this size has three deaths per year attributed to it from atmospheric pollution. On our reckoning this costs $600,000, neglecting non-fatal ill-health. The expected population

radiation dose is 400 man-rem, a dollar cost of $3,200 on the same basis. In tabular form:

TABLE 5

Health Costs for Fossil and Nuclear Power

| | Fossil Fuel | Nuclear Fuel | Ratio |
|---|---|---|---|
| All U.S. power | ~~535~~ 420 x $10^6$ | 1.6 x $10^6$ | 260 |
| 1000 MW unit | 6 x $10^5$ | 3.2 x $10^3$ | 187 |

This discussion of the public health costs of nuclear power is based only on authorized routine discharges of radioactivity to the environment; it does not reckon on accidents. Why this is so is indicated in Figure 3. This figure (Otway, 1971) plots the probability of accidental release of fission products from a pressurized water reactor of 1000 MWe against the magnitude of the release. It is clear that major incidents are likely to be so infrequent that it is difficult to associate them with a meaningful risk figure. Public damage can be roughly equated to the product of the magnitude of an event and its probability, and it is evident that it is low-release, higher probability events that have the most significance. If the existence of a threshold dose for radiation effects were accepted, this assumption would have to be reconsidered.

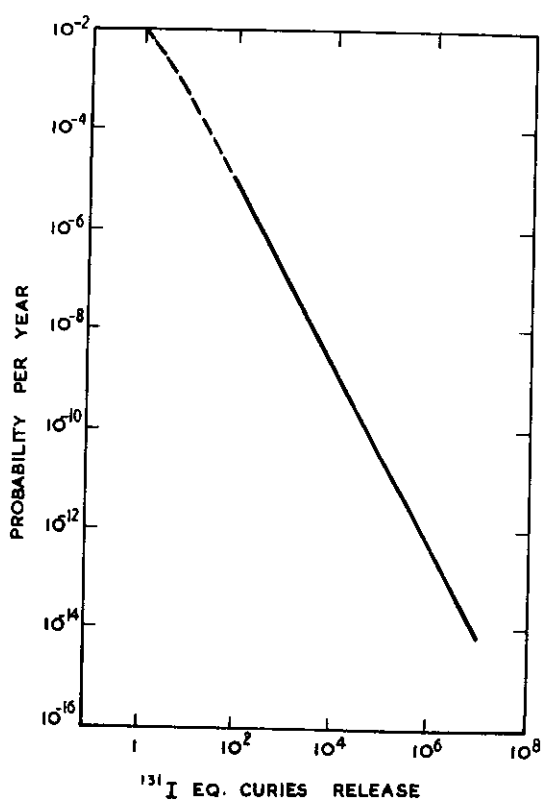


FIGURE 3 PROBABILITY AND MAGNITUDE OF ACCIDENTAL RELEASES

Atmospheric pollution from the combustion of fossil fuels leads to other costs besides those of health; these range from such minor consequences as increased laundry bills in dirty towns to corrosive attacks on all kinds of materials by sulphur dioxide and other pollutants. These costs have been estimated as being as high as £8 per head in the United Kingdom and $60 per head in the United States, but have not been taken into consideration here. Like the other figures in this paper, these are meant to be illustrative rather than definitive.

## CONCLUSION

I believe it is possible to make a comparative analysis of the environmental hazards of nuclear and fossil-fuel power, on a cost basis. It is likely that such a comparison would greatly favour nuclear power but much more information is necessary for a fully reasoned conclusion. In the interim it is necessary to remember that perfection is not possible; either approach demands some environmental risk and decisions need to be made objectively on the best available evidence.

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