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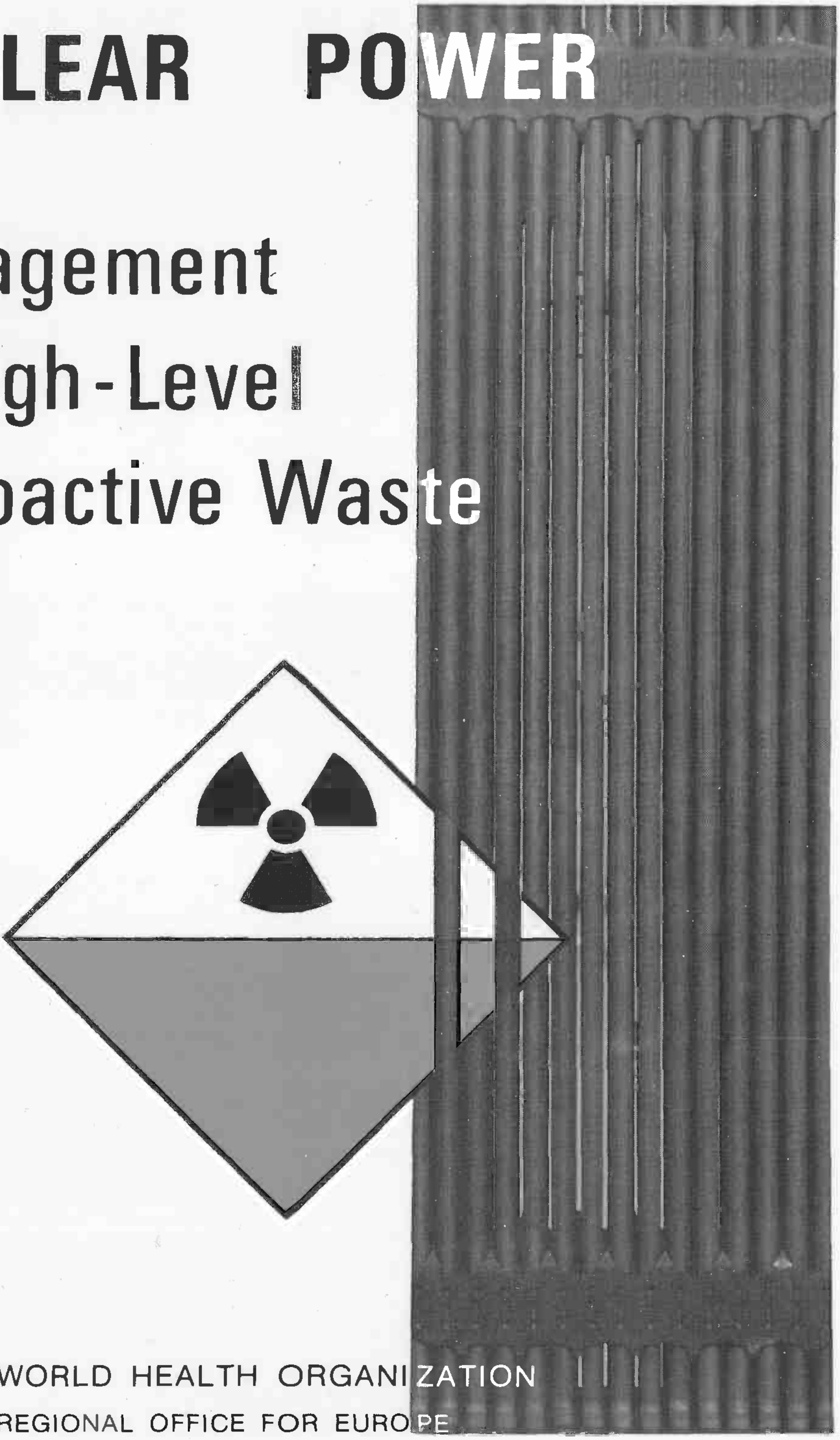
NUCLEAR POWER

Management of High-Level Radioactive Waste



WORLD HEALTH ORGANIZATION
REGIONAL OFFICE FOR EUROPE
COPENHAGEN

The World Health Organization is a specialized agency of the United Nations with primary responsibility for international health matters and public health. Through this Organization, which was created in 1948, the health professions of more than 150 countries exchange their knowledge and experience with the aim of making possible the attainment by all citizens of the world by the year 2000 of a level of health that will permit them to lead a socially and economically productive life.

The WHO Regional Office for Europe is one of six Regional Offices throughout the world, each with its own programme geared to the particular health problems of the countries it serves. The European Region has 33 active Member States,[a] and is unique in that a large proportion of them are industrialized countries with highly advanced medical services. The European programme therefore differs from those of other Regions in concentrating on the problems associated with industrial society. In its strategy for attaining the goal of "health for all by the year 2000" the Regional Office is arranging its activities in three main areas: promotion of lifestyles conducive to health; reduction of preventable conditions; and provision of care that is adequate, accessible and acceptable to all.

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MANAGEMENT OF HIGH-LEVEL RADIOACTIVE WASTE

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Detail of fuel assembly
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Report on a Working Group
Bruges, 2–6 June 1980

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NOTE

WHO policy in respect of terminology is to follow the official recommendations of authoritative international bodies, and every effort has been made in this publication to comply with such recommendations.

Nearly all international scientific bodies have now recommended the use of the SI units (*Système international d'Unités*) developed by the Conférence générale des Poids et Mesures (CGPM),[a] and the use of these units was endorsed by the Thirtieth World Health Assembly in 1977. The following table shows two SI derived units used frequently in this report, together with their symbols, the corresponding non-SI units and the conversion factors.

SI unit and symbol	Non-SI unit	Conversion factor
becquerel, Bq	curie, Ci	1 Ci = 3.7×10^{10} Bq (37 GBq)
sievert, Sv	rem	1 rem = 0.01 Sv

[a] An authoritative account of the SI system entitled *The SI for the health professions* has been prepared by the World Health Organization and is available through booksellers, from WHO sales agents, or direct from Distribution and Sales, World Health Organization, 1211 Geneva 27, Switzerland.

Introduction

The WHO Regional Office for Europe, in collaboration with the Government of Belgium, convened a Working Group on Health Implications of High-Level Radioactive Waste Disposal, from 2 to 6 June 1980. This was the third in a series of meetings arranged in Belgium on the health aspects of nuclear power production. The report on the first, a general review, was published in 1978 (*1*). The second and third were on health aspects of specific topics relevant to nuclear power production; the report of the former, on the transuranium elements, was published in 1982 (*2*).

The purpose of these meetings was to respond to the need for national health and environmental authorities in European countries to keep themselves and the general public well informed of the consequences for health of new developments in the peaceful uses of nuclear power. Although the development of nuclear power has declined in the past decade, despite the sharp rises in the cost of oil since about 1974, European countries are deriving an increasing proportion of their electricity supply from nuclear power reactors and the trend may be expected to continue (*3*). With this trend there is a natural and increasing concern about the possible exposure of workers and the general public to high-level radioactive waste and about the environmental consequences of its handling, treatment, transport, storage and disposal.

The report of the first meeting in this series describes the unit operations of the nuclear fuel cycle and the radiation doses that may be received during these operations, both by workers and by members of the general public. It also discusses the possible accidents that may occur and their predicted radiation effects, together with the possible consequences of the proliferation of nuclear weapons, sabotage and terrorism. There is a discussion of the implications for health in quantitative terms based on the studies of the International Commission on Radiological Protection (ICRP), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the US National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation (BEIR).

There have been recent developments in these fields which, though they do not materially affect the fundamental conclusions, do change the emphasis and importance associated with the health and other implications of nuclear power, and they have been taken into account in this report. Publications of ICRP (*4,5*) and BEIR (*6*) are of particular significance in this respect. Another important development since the first meeting in the series has been the publication of the working group reports and the Summary and overview of the International Nuclear Fuel Cycle Evaluation (INFCE) (*7*). The final plenary conference of INFCE, held in Vienna in 1980, concluded that nuclear energy production is expected to increase, that the specific needs of developing countries can and should be met, and that effective measures can and should be taken to minimize the danger of proliferation of nuclear weapons without jeopardizing nuclear energy supplies.

Several international organizations are concerned wholly or in part with the implications for health of radioactive substances and with their disposal. Of particular relevance to the topic of this report are ICRP and UNSCEAR, whose work is basic to an evaluation of radiation hazards; the International Atomic Energy Agency (IAEA), which has gathered and disseminated information, sponsored coordinated research programmes, and developed and formulated guidelines and codes of practice; and the Commission of the European Communities, which has organized and sponsored research on the disposal of high-level radioactive waste. A voluminous technical literature now exists.

In countries with active nuclear energy programmes there may be enough specialist advisers to be able to keep abreast of all this work and, indeed, to add to it by their own contributions, which extend and apply the fundamental conclusions of the international organizations. In other countries the same detailed knowledge and appreciation of the literature may not be available. In any case the knowledge may be confined to a narrow range of specialists often associated with the nuclear energy industry. In all countries there is a need for a balanced survey, independent of the nuclear energy industry, in which the literature is summarized and appraised in straightforward language. This report attempts to fulfil that need.

Radioactive aqueous waste, composed principally of fission products as well as some actinides, which is separated in the first solvent extraction cycle of the reprocessing of irradiated fuel, is universally classified as high-level radioactive waste. In some countries any other waste with levels of radioactivity intense enough to generate significant quantities of heat by decay is also so classified. Also, in some countries where reprocessing is not envisaged, the spent fuel from the reactor is classed as a waste, even though it contains fissile materials that could be removed and recycled; this spent fuel is then high-level radioactive waste. In this report the disposal of both the aqueous waste from the first extraction stage of reprocessing and spent fuel are considered. The other category of high-level waste is too vague for detailed consideration, but it is to be expected that the same general approach to its disposal would be applicable.

In any system for the management of high-level radioactive waste, storage will be provided for decay cooling and for use during the occasional plant shut-down. The final operation in the system will be long-term storage or disposal. In principle, there is a clear distinction between storage and disposal — disposal means that no further action (except environmental monitoring or restrictions on future use of the disposal site) is contemplated, whereas storage implies an intention to take further action at a later date in order to retrieve, treat, examine, or dispose of the waste. Although in practice the distinction may not be quite so clear, the difference in principle should be recognized.

As with most public health problems, an exact evaluation of the health aspects of the disposal of high-level radioactive waste is not possible, for much the same reasons that extrapolating from acute to chronic and from high to low doses is not. The justification for accepting the risks of exposure to ionizing radiation, despite the uncertainties of their evaluation, lies in balancing them against the health risks of not developing nuclear power; and the estimation of both sets of risk is subject to considerable uncertainty. Of course, this is not the whole story because in any attempt to assess the desirability of developing nuclear power, other factors such as social and economic effects have to be balanced too; these, however, lie outside the scope of this report.

Thus, while the report attempts to describe how the health risks may be estimated, it does not attempt to evaluate or even to describe fully the other factors that have to be taken into account in order to be able to justify the development of nuclear power. These other factors include the public's awareness or perception of the risks as distinct from the technical evaluation of the risk. Perhaps this report may help in bringing them together, though it is not deliberately concerned with this problem.

The close interaction of the technical and political arguments in this field requires a careful use of words and a clear appreciation of the limitations of the reasoning. In this report the basic recommendations of the ICRP, which are based on limited relevant data (though more extensive than for many, if not most, non-radioactive toxic materials) and extrapolation, are modified and reformulated in terms of the estimated risk to individuals and the collective risk to the general public. These estimates, which use projections of environmental and social factors far into the future, introduce other uncertainties. Inevitably the final conclusions are expressed as a probability or risk that a health effect or hazard will occur. There can be no assurance of absolute safety, only an estimate of the probability, however small, that the effect will occur.

This is the standard scientific approach. In some cases the probabilities can be fairly well calculated (the probability of being harmed in a traffic accident, for example) while in other cases (the very relevant probability of being harmed by the use of other energy sources may be cited) the estimate is more speculative. Essentially the approach of risk estimate in this report is no different from that in other aspects of government and public health control, though perhaps it is not always stated so explicitly.

The words "concern", "hazard", "probability" and "risk" have emotive connotations. In this report "concern" means "regard" or "interest" and is not used in the secondary and common meaning of "anxiety" or "solicitous regard". The disposal of radioactive waste is therefore a matter for concern but not for anxiety. "Hazard" is a potential deleterious effect but does not mean "peril" or "jeopardy" as it often does in ordinary usage; the deleterious effect may be quite minor. "Probability" is used in the mathematical sense, a measurable quantity of likelihood; it does not imply that the event may reasonably be expected to happen, as in the common use of the word "probable" and, indeed, an event having a probability of, say, one in a million is by no means likely to occur. "Risk" is also a measurable quantity: it is the product of the probability of the occurrence of an event and the probability of the harm if the event does occur. There is no implication of danger or peril when the word is used.

An insistence on the correct use and understanding of these words is not mere pedantry. This subject has important political undertones, and it is the normal practice in political debate to misrepresent the mis-statements of opponents. In the final decision-making when the technical, social, political and other factors, with all their uncertainties, are weighed up, it is important that there should be no ambiguity in the technical assessment. The considered view of the investigation into the Three Mile Island accident (*8*), that misplaced fear had greater implications for health than did the radiation, is a salutary reminder that the proper use of words and a clear understanding of health implications may be vitally important. In order to avoid any misunderstandings we have followed the definitions of IAEA (*9*) (see Annex 1).

The methods that have been suggested for the disposal of high-level radioactive waste are described briefly in this report with a fuller account of those that show most promise, and to which most effort is now being devoted. The way in which they may be evaluated for compliance with the ICRP recommendations as modified in the report is explained. Disposal in geological formations seems at present to be the most promising method, but disposal under the sea bed and possibly on the deep ocean bed deserves further research.

The Working Group considered 16 papers prepared by its members for the meeting and several shorter papers prepared during the meeting to clarify specific issues. The discussions took place in plenary session and in three subgroups formed to consider different aspects of the subject. Dr J. Schwibach was elected Chairman, Dr A. Lafontaine, Dr M. Kyrš and Dr F.L. Parker Vice-Chairmen, and Mr A.W. Kenny Rapporteur. Dr M.J. Suess acted as Scientific Secretary.

1

Conclusions and recommendations

The options for the disposal of high-level radioactive waste are part of the system of processing the waste for safe transport, storage and disposal, and for preventing the release of unacceptable amounts or concentrations of radionuclides into the human environment. They are based on the fundamental principles recommended by ICRP (*4*), i.e. that all radiation doses shall be kept as low as reasonably achievable, taking account of economic and social factors, and shall not exceed the appropriate dose limits now or in the future. This implies that the doses to future generations should be no greater than those acceptable at present.

The ICRP dose limits imply acceptance of a specific low level of risk to health, a level which, given what man voluntarily accepts from other beneficial but hazardous practices, is considered to be generally acceptable. The disposal methods will not isolate the radionuclides for ever, nor do they need to; the potential exposure of people, and therefore the potential overall risk, can be estimated by appropriate models. The risk inherent in the ICRP dose limits then becomes the standard against which these potential overall risks may be judged.

There has always been a greater emphasis on the safe handling and disposal of radioactive waste than of most if not all other toxic wastes. Despite the misgivings of some sections of the public, who doubt man's ability to solve the problem and perhaps misinterpret the emphasis on safety as a reason for fear, most knowledgeable workers in this field believe that the technology required for the safe disposal of radioactive waste is already available. What remains is to decide which of several approaches should be selected, and when to implement them.

There are two characteristics of radioactivity that help in the safe management, storage and disposal of radioactive waste. First, decay of the radionuclides greatly reduces toxicity and heat generation with time; second, the ease of adequate monitoring, detection and measurement allows the correction of abnormal conditions before an unacceptable situation develops. This has important implications for the concept of disposal of high-level radioactive waste, which implies that the waste is abandoned with no intention to retrieve or to provide for more than routine surveillance for a limited period. The repository site is not necessarily abandoned and may be subject to administrative control after disposal. On the other hand storage, which is generally a step in the process of waste management, implies retrievability and an intention to carry out further operations.

Methods for the management and interim storage of high-level radioactive waste are in use and are well proven. Disposal methods have not yet been selected, still less demonstrated, but extensive research and development are being carried out in many countries to ensure that the necessary technical experience will be available when the time for decision arrives. The technical problem is to ensure adequate isolation over the required period of time, so that the acceptable risk to health is maintained throughout that period.

Of the options for the disposal of this waste, placement in vitrified form in suitable geological formations has received most attention. The placement would be in suitably engineered facilities to avoid local overheating. The multibarrier approach — the disposal of immobilized waste in canisters, with or without additional absorbent material, in geological formations — appears to offer good assurance of long-term isolation from the human environment.

Two of the options for disposal would probably require amendments, one to the London Convention on the Prevention of Marine Pollution by Dumping of Waste and Other Matter and the other to the Antarctic Treaty of 1959. While recognizing the political difficulties that might attend proposals for amendment, we consider that they should not hinder the proper technical assessment of the options and (if the assessment were to demonstrate their feasibility) their development. International organizations and agreements should not limit the options for waste disposal.

Two systems for the complete elimination of the waste, or at any rate of the actinides, have been proposed, but the outlook for these options is not promising.

No single characteristic alone will determine the behaviour of the waste in its repository; the method of treating the canister, the absorbent or migration retardant, the geological and other environmental barriers should all be analysed and the whole system evaluated in relation to other systems and to health standards. A suitable disposal system is one that provides the assurance that the waste will be safely isolated from the biosphere for a long time. Conservative engineering practices and multiple barriers are expected to be able to compensate for the lack of knowledge and degree of uncertainty involved in predicting what may actually be required of a repository. Thus the waste can be isolated so that it will not entail unacceptable health risks from radiation at present or in the future.

Transportation will be included in the overall evaluation of the system. Wherever practicable, it is desirable to locate the fuel reprocessing and waste processing facilities together, including the repository facility itself. It can all then be managed on one site with minimum handling and transportation (which in principle should reduce radiation doses to workers and the general public) and with appropriate security precautions against malicious acts.

Proper site investigation and selection are of paramount importance for establishing sufficiently favourable geological and hydrogeological conditions. Waste repositories may not isolate the waste from the biosphere for ever and, indeed, it is not necessary that they should do so; the multiple engineered and natural barriers in the repository system are expected to restrict the release of radionuclides to the human environment to acceptable amounts and concentrations so that the implications for health of the disposal of high-level radioactive waste will be so low as to be acceptable. Some conservatism in selecting the parameters used in the assessment of high-level radioactive waste disposal is desirable because of the uncertainty of predicting the behaviour of the geosphere and biosphere in both the near and distant future. The dynamics of the environmental transfer of long-lived natural radionuclides and of stable elements deserve to be studied carefully, both in the geosphere and in the biosphere, as analogues of some of the man-made radionuclides. In particular, careful attention should be paid to establishing the physicochemical forms of radionuclides in the relevant environmental phases; not only are appropriate analytical methods lacking in many cases, but those available have rarely been applied at the low atomic concentrations that are appropriate in this case.

The protection of the public against exposure to ionizing radiation is the overriding health concern in the disposal of high-level radioactive waste. It is recommended that the acceptability of waste disposal methods be determined on the basis of the effects of predicted doses on individuals and populations, while also taking into consideration the probability of their occurrence. In performing the calculations of predicted doses, it is necessary to take into account the uncertainties of many parameters, which will lead to ranges of results rather than precise answers. The probability of occurrence will be determined mainly by the probability of occurrence of the initiating event. The selection of a waste disposal option should follow a sequential procedure incorporating the following steps.

1. Apply appropriate predictive models to estimate the potential doses to individuals in critical groups and the collective doses to populations at all future times. These models should incorporate estimates of the probability of their occurrence.

2. The probability (risk) of the effects on health of the estimated doses and their probability may then be assessed by appropriate standards.

3. If more than one disposal option meets the standards, selection should be based on a comparison of the collective dose commitments calculated to cut off at a selected time in the future (10^4 years, for instance) and the probabilities of their occurrence.

4. In the selected option, predicted collective dose commitments should be reduced as low as reasonably achievable, taking economic and social factors into account.

In view of the importance of this subject, national and international bodies should give high priority to their programmes of work on the development of such standards of acceptability. Health effects predicted as a result of the disposal of high-level radioactive waste should be compared with those predicted as a result of other activities, such as alternative methods of generating power, the use and disposal of other toxic substances, or natural radiation doses.

Guidelines for the licensing, operation and final closure of repositories are being prepared in parallel with the development of waste disposal methods. Records and inventories for these sites should be maintained by national authorities and should contain all the information necessary for the future. Governments and international organizations should encourage the exchange of information and the latter should establish an international register of high-level radioactive waste repositories.

The disposal of radioactive waste into international waters, territories and space should be subject to international agreement and supervision, with the participation of international organizations and the national authorities concerned.

National and international organizations should be encouraged to support and coordinate research and development in order to improve the assessment of the parameters required for evaluating the impact on health of all sources of energy, so that proper comparisons of the various energy options may be made.

Advisory services and expertise should be made available by international organizations at the request of governments for the planning and implementation of national waste disposal programmes.

2

High-level radioactive waste

Nuclear reactors derive their energy from the fission of nuclear fuel, the splitting of the fuel atoms into two or more smaller atoms. The fuel (which may be normal or enriched uranium, or a mixture of uranium and plutonium, either as elements or as oxides) is contained in metal cans or cladding in the reactor. In the reactor, some of the fuel (uranium and plutonium) is fissioned, generating the fission products, some is converted by neutron absorption into heavier (transuranium) elements and some remains unaffected.

Although the cans are usually made of stainless steel, zirconium alloy or magnesium alloy, which are materials chosen for their low neutron absorption capacity, they nevertheless become very radioactive in the intense neutron field of the reactor owing to the formation of activation products, radionuclides generated from the elements of the canning material by neutrons. For the most part these are of relatively short half-life compared with many fission products and do not contribute appreciably to the fuel element (i.e. fuel and can) activity in the long term.

A fuel element often includes a number of fuel pins held in a bundle by a structure. This may be metallic, with spacers for holding the fuel pins apart in the reactor, and the pins may be shaped externally to produce appropriate coolant flows and aid heat transfer. The assembly with its spacers and structural parts is an additional source of activation products.

Whatever the type of nuclear reactor, a method for the treatment of the spent fuel has to be chosen when the fuel assembly is withdrawn from the reactor. The simplest option is to store it, either indefinitely or until substantial decay has occurred; storage can be in water-cooled or air-cooled facilities. Some cooling provision is essential during the first few decades because the irradiated fuel elements are significant sources of heat while the fission products undergo radioactive decay. This option has been explored in Canada and more recently in the United States, during the moratorium on fuel reprocessing pending a decision on the nuclear fuel proliferation risks of the various fuel cycles.

This storing of irradiated fuel without reprocessing is called the "stowaway fuel cycle". At first sight it would seem to avoid the problem of plutonium proliferation since the plutonium is locked in the highly radioactive irradiated fuel and its extraction for military purposes would require sophisticated and elaborate equipment which is unlikely to be widely available. On the other hand, the activity decays rapidly and after a few decades it would no longer provide the same protection. Moreover, in an energy-hungry world, it seems unreasonable to lock up the fissile material instead of extracting it for reuse as an energy source (*7*).

Fuel assemblies from the stow-away fuel cycle would constitute high-level radioactive waste if they were disposed of with no plans for retrieval. This is called the "throw-away fuel cycle" but, to date, it has not been used. All such fuel assemblies have been stored under conditions which would allow retrieval.

Another option, after removal of the fuel assemblies from the reactor, is to reprocess them and recover the unfissioned uranium and plutonium for further use in a nuclear reactor (*10*). Reprocessing is usually effected by dissolving the fuel assemblies in nitric acid and separating the constituents by solvent extraction of the acid solution. Initially, the assembly and cladding can be mechanically stripped from the fuel, which then goes forward to the nitric acid dissolving plant, or the fuel elements can be chopped up and leached with nitric acid, leaving the assembly and cladding undissolved. In either case the waste (i.e. the cladding and the assembly parts), which may contain substantial amounts of irradiated fuel and fission products (depending on the efficiency of the separation processes), is no longer high-level radioactive waste according to our definition and is not considered further in this report.

Uranium and plutonium are separated from the fission products by putting the nitric acid solution of fuel into contact with an immiscible solvent such as tributyl phosphate in an organic diluent. The extraction is highly efficient. Over 99.9% of the fission products remain in the aqueous phase and virtually all the uranium and plutonium are extracted by the solvent together with most of the other transuranium elements. The aqueous solution, which is often referred to as the raffinate, is high-level radioactive waste by our definition. The solvent solution is then subjected to further treatment to separate the remaining fission products from the uranium and plutonium. These operations produce other wastes which are part of the medium-level and low-level radioactive wastes of reprocessing and do not fall within our definition of high-level radioactive waste.

For the purpose of this report, high-level radioactive waste is:

(*a*) the raffinate (waste aqueous liquor) from the first extraction stage in the reprocessing of irradiated fuel elements; and

(*b*) the irradiated fuel elements when declared to be waste as part of a throw-away fuel cycle.

These two wastes, raffinate and irradiated fuel elements, both contain virtually all the fission products, although the raffinate loses minor amounts of gaseous fission products released during the acid dissolving and some fission products extracted by the solvent in the first extraction stage.

If reprocessing is not performed, the irradiated fuel that has to be stored or disposed of amounts to about 28 tonnes a year from an installed capacity of 1 gigawatt of electricity: the size of a large modern power station supplying the needs of a population of about a million in the more developed countries. As already stated, no fuel has been disposed of yet, but is all in store pending a decision.

The raffinate consists primarily of an aqueous solution of the nitrates of the fission products and actinides. It will also contain:

(*a*) a small amount of uranium and plutonium which escapes recovery, generally less than 1% of that in the spent fuel;

(*b*) other components of the fuel that are soluble in nitric acid;

(*c*) soluble "poisons", added to prevent critical situations developing in the dissolver; and

(*d*) minor amounts of processing chemicals and plant corrosion products.

To reduce its volume for more economical storage in plant or pending disposal, the raffinate is concentrated by evaporation and then stored in specially designed stainless steel tanks. About 10 m^3 of concentrated waste is produced per annum for each gigawatt of electricity. Of its dissolved solids about half consists of fission products. The principal activities are given in Table 1, which refers to waste about 10 years old and assumes that reprocessing takes place 150 days after removal from the reactor with 99.5% efficiency of separation. The annual production of activity per gigawatt of electricity is given for each radionuclide with a half-life greater than 25 years. The table also includes daughter products from the decay of the actinides formed in the reactor; some of these activities (such as that of radium-226) increase for a period as the waste ages owing to growth from the precursors, but eventually a secular equilibrium is reached. For the first few centuries the fission products as a whole contribute most to the total activity, but they decay more quickly and ultimately it is the activity of the longer-lived actinides that dominates.

The high-level radioactive waste from the reprocessing of nuclear fuel used for defence purposes can be different from that just described. In particular the first high-level radioactive waste produced at Hanford in the United States during World War II was the product of a markedly less efficient separation process than those now used. Large volumes of alkaline waste were stored in tanks not designed or constructed to standards comparable to those now used. Some of these old tanks have leaked but, thanks to prudent siting with a series of natural barriers against radionuclide migration from the tank subsoil, any potential radiological hazard will be eliminated by radioactive decay before the activity reaches the Columbia River. Essentially all the liquid waste remaining in these older tanks has been converted to salt cake and new double-walled tanks have been put into service. The experience with this waste is in no way similar to what may be expected of the storage of modern acid waste in tanks of high specification.

Table 1. Principal activities in high-level waste: annual generation of waste aged for 10 years per gigawatt (electrical) of installed generating capacity[a]

Fission products			Actinides		
Nuclide	Half-life (years)	Bq/year	Nuclide	Half-life (years)	Bq/year
^{79}Se	6.5×10^4	3.7×10^{10}	^{226}Ra	1600	1×10^5
^{87}Rb	4.7×10^{10}	1.8×10^7	^{229}Th	7340	4.0×10^3
^{90}Sr	28.6	5.5×10^{16}	^{230}Th	7.7×10^4	1.9×10^7
^{93}Zr	1.5×10^6	1.8×10^{12}	^{232}Th	1.4×10^{10}	30
^{99}Tc	2.1×10^5	1.3×10^{13}	^{231}Pa	3.2×10^4	2.3×10^7
^{107}Pd	6.5×10^6	1×10^{11}	^{232}U	71.7	8.1×10^7
^{126}Sn	1×10^5	5.1×10^{11}	^{233}U	1.6×10^5	1.4×10^7
^{129}I	1.6×10^7	3.5×10^{10}	^{234}U	2.5×10^5	6.2×10^9
^{135}Cs	2.3×10^6	2.7×10^{11}	^{235}U	7.1×10^8	8.1×10^7
^{137}Cs	30.2	8.1×10^{16}	^{236}U	2.4×10^7	1.3×10^9
^{151}Sm	90	1×10^{15}	^{238}U	4.5×10^9	1.5×10^9
			^{237}Np	2.1×10^6	3.2×10^{11}
			^{238}Pu	87.8	9.6×10^{13}
			^{239}Pu	2.4×10^4	1.5×10^{12}
			^{240}Pu	6540	4.4×10^{12}
			^{242}Pu	3.9×10^5	6.6×10^9
			^{241}Am	433	1.5×10^{14}
			^{242}Am	152	3.7×10^{12}
			^{243}Am	7380	1.7×10^{13}
			^{243}Cm	28.5	4.0×10^{12}
			^{244}Cm	18.1	1.6×10^{15}
			^{245}Cm	8500	2.6×10^{11}
			^{246}Cm	4730	5.5×10^{10}
			^{247}Cm	1.6×10^7	2.6×10^5

[a] Based on a light-water-cooled reactor with an average energy generation of 33 000 MWd per tonne of fuel and an average power of 30 MW per tonne; reprocessing after 150 days with 99.5% recovery of uranium and plutonium; thermal efficiency 33%; availability of reactor 70%.

Most of the high-level radioactive waste in aqueous form that has been produced by the reprocessing of nuclear fuels in various countries is now stored either as liquid or as salt cake in underground tanks. The size of the tanks varies from 50 m^3 to 500 m^3. Stainless steel tanks are used for acid waste; mild steel tanks are commonly used for waste that has been alkalified.

An important characteristic of high-level radioactive waste is the heat output associated with its radioactive decay. Cooling systems have to be provided to control the temperature of the waste in the tanks, which would otherwise reach boiling-point in the early stages of storage. As the waste ages, the generated heat decreases and the cooling requirements ease. For example, one year after discharge from a modern light water reactor, the heat generation is about 10 kW/m^3 of concentrated waste; this may have dropped by an order of magnitude 10 years later. Heat removal is achieved either by water flowing through cooling coils inside the tanks, which keeps the temperature below 65 °C, or by allowing the liquid to boil and the steam to condense.

The storage of high-level radioactive liquid waste is now a routine operation which has been practised for about 35 years with no recorded leak into the ground (with the exception of the old storage tanks at Hanford). It is a well understood operation which can continue to be used safely in the interim before solidification is adopted (*11*). Indeed, even when a policy of full-scale solidification of waste is implemented, a comparatively small provision for liquid storage will still be needed, to cover the interval of at least 5 years between reprocessing and solidification, though the liquid storage capacity could be minimized by storing the irradiated fuel for a "cooling" period before reprocessing.

In the future, storage of high-level radioactive liquid waste for more than a few years will probably be eliminated through its conversion to solid form. The object of solidifying is to make controlled storage easier and cheaper: it is justified on economic grounds alone but it will also make storage safer because the waste is immobilized. Interim storage of this solidified waste on the site of the fuel reprocessing and waste solidification plant will probably be necessary to allow radioactive decay of most of the radionuclides with short and intermediate half-lives prior to disposal. During this interim storage, cooling with either air or water will be necessary.

Many methods have been proposed for the interim storage of solidified high-level radioactive waste in man-made structures at or near the surface of the earth. "Engineered storage", as this approach is called, enables cooling to be provided and continuous surveillance to be maintained in the early years when heat generation is at its greatest. Its use also provides more time for detailed evaluation of the many options available for ultimate disposal.

The solidification or immobilization route that is most highly developed is the conversion of the liquid waste into a block of alkali borosilicate glass cast into a stainless steel container (*12*). Leading this development is the AVM plant, which has been vitrifying high-level radioactive waste on an industrial scale at Marcoule in France since June 1978. This follows the earlier PIVER batch process developed by the French and operated successfully at the same plant for 11 years, during which time some 164 containers of vitrified waste (12 tonnes of glass, 2×10^{11} Bq) were produced and are now housed in an air-cooled store. By the end of 1979 some 170 m^3 of high-level radioactive waste had been solidified and cast into canisters 0.5 m in diameter and 1 m tall, each containing about 0.36 tonnes of glass. Assuming that the finished glass incorporates 25% of the dissolved solids of the waste in the form of oxides, each gigawatt of electricity will eventually yield about 10 tonnes of glass per year.

The advantages of glass as the solidification medium (*13*) are:

(*a*) it can readily incorporate almost all the fission products and other materials in the waste, while the few that do not dissolve are dispersed as inclusions;

(*b*) it has a reasonably high capacity for the waste — typically 25–30% by weight, as oxides, can be incorporated;

(*c*) it can tolerate the variations in waste composition that will inevitably occur in an industrial plant;

(*d*) it is relatively inert chemically (in particular, it has adequate resistance to leaching by water at moderate temperatures), it has zero vapour pressure, and it is relatively stable to ionizing radiation; and

(*e*) a convenient and compact product is obtained directly by casting the melt in a container.

Alkali borosilicate glasses possess all these advantages and can also be made at temperatures of about 1100 °C, which means that the vitrification plant can be constructed of conventional stainless steel, which is a ductile engineering material of proven performance. The reliability of equipment is vital in processes handling highly active materials, since it reduces the exposure of maintenance workers and operators (*12*).

Phosphate glass received considerable attention in the past as the solidification medium. However, it is more difficult to design plant for phosphate glass systems because of corrosion problems and, since the properties of the product are no better than those of alkali borosilicate glasses, work on them has generally been suspended. Zinc borosilicate glasses have been comprehensively developed in the United States but they are more susceptible to loss of durability on devitrification than alkali borosilicate glasses.

Four steps are involved in the conversion of high-level radioactive liquid waste to glass:

(*a*) the evaporation of water and nitric acid;

(*b*) the calcination of the nitrates to oxides;

(*c*) the reaction of the oxides with added chemicals to form glass; and

(*d*) the casting of the molten glass into a container.

In the French AVM process, the first two steps are performed together in a rotary calciner. The calcine is fed with added glass frit into an Inconel pot melter at up to 1150 °C and the glass is then periodically discharged into canisters (*7*). No other country has yet put into operation the routine vitrification of its high-level radioactive waste. The United Kingdom is to adopt the AVM process, preferring it to its own HARVEST solidification process, which uses single-stage pot vitrification but has not been fully developed. Belgium, the Federal Republic of Germany, Italy, Japan and Sweden are also considering vitrification processes and India is about to start up a vitrification plant. At present in the United States there is no reprocessing of nuclear power fuel and so attention is concentrated on the vitrification of high-level radioactive waste from defence work, for which the first full-scale plant is planned at Savannah River for the end of the 1980s.

One process that has been comprehensively developed in the United States is the Spray Calciner plus In-Can Melting. As in the French process, the first two steps are carried out in the calciner which then discharges calcine directly into the canister where, with added glass frit, vitrification takes place: that is, the third and fourth steps occur together. Most of the process development work in the United States is now focused on the Joule Heated Ceramic Melter system, which is based on a type of electric melter widely used in the glass industry where the glass is heated directly with electrodes. It can be operated either with liquid feed, when the first three steps all occur in a single operation, or with calcine, when the first two steps are performed first and only the third step is performed in the melter (*14*).

Two other vitrification processes being investigated in the United States are at a much earlier stage of development. The first makes use of techniques developed in fibre optics technology. By means of a phase separation technique, a high-silica porous base is made which is then mixed with high-level radioactive waste. Incorporation is achieved by heating the mixture to 900 °C, when the pores close up as the base glass sinters. This glass is more durable than the alkali borosilicates. In the second process high-level radioactive waste is converted to glass in the form of marbles, which are coated with inert material such as pyrolytic carbon or alumina and then dispersed in a metal matrix such as lead or aluminium inside a stainless steel canister. This process is intended to improve durability by the inclusion of the additional barriers, but caution is necessary since after a few centuries the lead could be the most hazardous component of the product (*15*).

The most straightforward solidification process for high-level radioactive waste, requiring no additives, is to heat the waste liquor, driving off the water and the nitric acid, and to calcine the nitrates into oxides, giving a brown powdered calcine. This technique has been used on an industrial scale at Idaho Falls in the United States where a fluid bed calcination plant has been in operation since 1963. Some 1700 m^3 of calcine have been produced and stored in stainless steel silos. The liquor, like the other defence waste in the United States, consists principally of dissolved cladding and process chemicals such as fluorides of ammonium, zirconium and calcium, with only about 1% of fission products. However, the transport of waste as powdered calcine is unlikely to be permitted and further processing would probably be required before disposal was possible. Conversion to borosilicate glass is being studied.

During vitrification, some of the radionuclides (e.g. ruthenium and cesium) are volatilized and some material is released as an aerosol. These are trapped in conventional, highly effective off-gas treatment systems consisting of condensers, wet washers, gas drying equipment and aerosol filters (HEPA). These systems are normally overdesigned for normal operation in order to provide effective protection in case of accidental release. The waste produced in the off-gas treatment system is handled as low-level or medium-level radioactive waste within the overall plant waste management.

A criticism levelled against glass as the immobilization medium is that, because it is in a metastable thermodynamic state, devitrification is always possible and would lead to a deterioration of the properties of the solidified waste. In fact, the borosilicates now adopted and available in Europe and the United States have been shown to be virtually unaffected in dry storage conditions. Nevertheless, several programmes for the development of improved immobilized waste forms are in progress and may provide adequate alternatives to glass. These alternative processes use calcine as a basis. In the United States' programmes "Supercalcine" is made by heating to 1100 °C a mixture made by a 23% addition of selected constituents such as silica, lime, alumina and strontium oxide. Insoluble crystalline phases are formed in which the radionuclides are fixed and the product is hot-pressed to compact it. In the Australian programme "Synroc" is made by heating 10% calcine and 90% a mixture of titania, zirconia, alumina, lime and barium oxide to 1300 °C. Because the principal crystalline phases formed (hollandite, zircorolite, perovskite) are known as very stable minerals, it is claimed that Synroc is especially suitable for the disposal of high-level radioactive waste (*16*).

Glass ceramics have also been proposed for immobilization. Additions such as titania are made to the basic borosilicate glass composition to encourage maximum crystallization so that the final product is more thermodynamically stable.

It may be concluded that a technology exists, based on the vitrification process, for converting aqueous high-level radioactive waste into an immobilized form (*17*). One vitrification process is now being used on an industrial scale. Other immobilization approaches are being investigated but are technically more complex, since they require higher manufacturing temperatures and extra mechanical operations. Many of the alternative immobolized waste forms are claimed to be superior to borosilicate glass for disposal because they are more durable, but they have yet to be thoroughly tested.

Thus, the technology for the immobilization and interim storage of high-level radioactive waste is available. The technology for handling, transport and placement of treated waste is a straightforward adaptation of the established techniques for radioactive materials. Proposals have been made and are under investigation for isolating or disposing of the treated waste by placing it in geological formations remote from the biosphere in order to reduce the already low probability that it will ever enter the human environment in unacceptable quantities or concentrations. To assess the hazard of these proposals, we will proceed first to a discussion of the health protection objectives of these operations and then to a description of the procedures used to estimate the probability of human exposure resulting from the proposed methods of disposal (i.e. the placement of treated high-level radioactive waste in selected engineered or natural repositories with no plans for its retrieval).

In summary, there are three main fuel cycle options for the management of high-level radioactive waste: the stow-away cycle, the throw-away cycle, and the reprocessing cycle. The stow-away cycle defers the problem of treatment and ultimate disposal, and does not offer a final waste management solution. The throw-away cycle appears simple at first sight because it has fewer processing stages, but it does not recover uranium and plutonium for further energy generation. The presence of all the plutonium in the waste also raises major problems of toxicity and criticality over long periods, and unless extensive conditioning techniques are employed the spent fuel will present a large surface for leaching and will not be chemically stable in many natural environments. Reprocessing with vitrification, on the other hand, does meet many of the requirements of modern waste management: it ensures that the waste form is suitable for disposal, that the amount of plutonium disposed of in the environment is minimized, and that energy conservation is achieved.

3

Objectives of health protection

ICRP framework

The discovery of X-rays and of radioactivity opened the door for their widespread use in medical diagnosis and treatment, but it was soon found that their extensive use could damage human tissues and cause genetic change. In the 1920s two radiation protection agencies were formed to study their harmful effects and to provide guidance for their safe occupational use: ICRP and, in the United States, the National Council on Radiation Protection and Measurements (NCRP).

After World War II, with the increased use of radionuclides and the likely use of nuclear power, considerable scientific effort was put into understanding the fundamental processes of ionizing radiation in human tissue and into providing firmer foundations for guidelines for maximum permissible doses, not only for occupational workers but also for the general public. UNSCEAR was formed in 1955 to provide information on the levels of human radiation exposure and their effects.

The effects of ionizing radiation on human health which these bodies are concerned with may be classified in two ways (*2*).

1. Stochastic and non-stochastic.

2. Somatic and non-somatic.

Stochastic effects are those for which the probability of the effect occurring increases with increasing radiation dose, with zero probability only at zero dose. The severity of a stochastic effect is not dependent on the dose. Non-stochastic effects are those for which there appear to be threshold doses below which these effects will not occur. The severity of a non-stochastic effect increases with the dose above the threshold. Somatic effects are those which manifest themselves in the exposed individual, while non-somatic effects (or genetic effects) are those which occur in the descendants of the exposed individual.

Cancers are one of the stochastic somatic effects of irradiation. Lens opacity, impaired fertility and non-malignant skin damage are non-stochastic somatic effects. Genetic effects are stochastic non-somatic effects and teratogenic effects are non-stochastic non-somatic effects. Even though exposure to high-level radioactive waste could be lethal, safety designs and practices are such that the radiation doses encountered by those handling it are well below the thresholds for non-stochastic effects, while the doses that might be received by individual members of the public from storage and disposal will, in general, be orders of magnitude below those received occupationally. Because of the low individual doses expected, the only effects that need to be discussed in this report are stochastic ones.

The evidence that the above-mentioned committees have reviewed in order to formulate guidelines for controlling radiation exposure derives from human exposure and from animal experiments. The human evidence includes the Japanese survivors of the atomic bombs, rheumatoid spondylitics treated with ionizing radiation, and luminous-dial painters. All these groups received relatively high doses of ionizing radiation; essentially no detectable effects have been observed in persons who have been exposed to low doses of ionizing radiation (*4,6,18*).

To estimate the rate of somatic effects at chronic, low dose rates from the observed data of acute exposure, an assumption has to be made about the relationship between dose and effect. The assumption that has almost universally been made, with the deliberate intention of not underestimating the effect, is that the risk of the somatic effect is directly proportional to the dose: the linear relationship assumption. BEIR (*6*) concluded quite recently that "for most radiation-induced solid cancers, the dose–response relationship for low to intermediate doses of LET radiation is best described by a linear–quadratric function of dose". (Low-energy-transfer (LET) ionizing radiation is that for which the density of ionized tissue along its path is relatively low, essentially X and gamma radiation as opposed to alpha radiation.) This would predict a cancer mortality about half that which a linear dose effect assumption would give, the assumption used in an earlier BEIR report (*19*).

Given the complexities and uncertainties of the calculations and the assumptions involved, the ICRP, UNSCEAR and BEIR are in good agreement in their estimates of about 10 000 cases of cancer per million person-Sv, a figure derived virtually direct from the approximately 200 cases of cancer in the Japanese atomic bomb survivors, who are estimated to have been exposed to about 20 000 person-Sv. This figure may be taken as an upper estimate. At this level, as BEIR points out, "a distinct carcinogenic effect could be discernible for the large doses that may be associated with lifetime occupational exposure". Several studies that indicated a cancer incidence greater than the linear assumption would predict were also reviewed in the 1980 BEIR report (*6*), but their conclusions were rejected on the basis of the methodology used, which was open to criticism.

The estimates of genetic effects in man are made in two ways. In one, radiation-induced mutation rates, derived from experiments with mice, are used to estimate the radiation-induced mutation rates in man compared with his natural mutation rates. In another, data on radiation-induced mutation rates for genes or chromosomes in mice are applied with suitable corrections to estimate directly the rate of gene or chromosome changes in man. The effect estimated by these committees is in the range 500–5600 additional genetic disorders per million live births in the first generation per sievert of parental exposure before conception, compared with a natural 100 000 per million. The genetic effects of continuous population exposure should theoretically increase to an equilibrium over time (5–10 generations for the most important effects, longer for others); the BEIR estimate is 6000–110 000 genetic disorders per million live births per sievert of parental exposure before conception at equilibrium. These may be upper estimates since no evidence of extra genetic effects has been observed in Japanese atomic bomb survivors or in mice irradiated at 2 Sv per generation over many generations.

It will be clear from this brief outline of the assumptions made in the estimates that the results are approximate and should be used only for comparative purposes. There is a minority view that the assumptions are not as conservative as most experts in the field believe. It is important to appreciate that, although the estimates are approximate, the upper bounds of the estimates are set by the observed relationship between the natural incidence of cancers and genetic effects, and the natural background of ionizing radiation, which are more accurately known.

The translation of this fundamental health relationship into principles for controlling the practices that can expose humans to ionizing radiation is the concern of ICRP, which is continually reviewing and modifying its recommendations. The framework for these principles has been restated (*4*) as:

- no practice shall be adopted unless its introduction will produce a positive net benefit (justification principle)
- all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account (optimization principle)
- the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the ICRP.

This framework is designed to help in the planning of practices in which workers and/or members of the general public are expected to be exposed to ionizing radiation. The objective in the storage or disposal of high-level radioactive waste is to isolate it from the general public. Given the long time-scale and the uncertainties of predicting events so far in the future, there can be no absolute guarantee that this will be achieved. Despite the difference in objectives, the fundamental concern that governs the technical approach to the processing and disposal of high-level radioactive waste is the same, namely, the protection of workers in the reprocessing and disposal operations and of members of the public from unjustifiable radiation exposure. The high radioactivity level of the waste calls for strict standards and thorough examination of the proposals for disposal. The same basic principles should apply to the disposal of high-level radioactive waste as to any other practice that has the potential to expose workers and members of the public to ionizing radiation. These principles should conform with the fundamental principles of the ICRP framework.

Justification principle

The storage or disposal of high-level radioactive waste is a necessary consequence of nuclear power generation. The decision to generate power in this way will have been taken as a matter of government policy, in which the needs of the community will have been identified and a choice made between the options available. The ICRP justification principle applies to this choice of options, which should have been made after full consideration of their advantages and disadvantages to the community. The identification and evaluation of the consequences of the storage or disposal of the high-level radioactive waste produced will be part of this decision-making process. The potential detriment from the disposal of high-level radioactive waste may, to a small extent, affect the decision as to whether the generation of nuclear power is justified. The generation of high-level radioactive waste is an inevitable consequence of government decisions to develop this form of energy and, therefore, cannot be justified separately.

It is sometimes contended that a decision to develop nuclear power cannot be made properly unless a process for the disposal of the high-level radioactive waste has been demonstrated, which implies, for instance, that a full-scale plant has been operated successfully for some time. It will be evident, however, that the decision on the options for the generation of energy must be based on predictions of the probability of future events; the uncertainty associated with the disposal of high-level radioactive waste is comparatively low, less than that of many other factors in the decision-making process. Experience with the storage of vitrified waste allows the confident prediction that it could be adopted for a sufficiently long time to permit adequate disposal methods to be developed.

Optimization principle

The second principle in the ICRP framework of dose limitation is that of optimization. This requires that radiation exposures be kept as low as is reasonably achievable, taking into account economic and social factors as well as effects on health. One way of assessing whether radiation doses have been reduced to levels that are as low as reasonably achievable is to apply techniques of cost–benefit analysis (*20*). This requires an assessment of the costs of the disposal operation and of the cost associated with the radiological detriment from the disposal. The latter requires the assignment of costs to a wide range of effects on the health of present, future and remote populations. The optimal level of radiation protection is the level that minimizes that total cost to society, including both the costs of protection and control and the monetary equivalent of the potential detriment to health.

There has been considerable discussion about how detailed these calculations need to be, and whether the same weight should be given to doses that may affect problematic populations in the remote future as to those that may affect present populations and their close descendants. Discounting and other techniques have been proposed in order to accommodate this and similar views. It is doubtful whether such elaboration can be justified. The rigour with which the technique is applied should be commensurate with the importance of the doses likely to be received from the different waste disposal options, and of the costs entailed. Normally only simple assessments will be justified.

Indeed, an alternative approach has been proposed in which the important effects on health are set out with qualitative, descriptive assessments of their importance and ordered semi-intuitively. A comparison with the monetary costs of the options may then give a quick, simple assessment of the optimal level of radiation protection.

The optimization approach is likely to prove especially useful when comparing options for waste disposal; the comparison may be reasonably accurate even though the actual quantifications may not be very precise. The comparisons should include the following:

— the doses to workers

— the doses to members of the public

— the distribution of doses to persons in the exposed group

— the distribution of these doses over time and their expected probability (frequency of occurrence)

— the economic costs of disposal alternatives

— other non-radiological environmental impacts.

The comparison should take into account all the steps in the disposal systems, including transportation and interim packaging and storage.

Dose limits

The third principle in the ICRP framework relates to the dose limits recommended for particular circumstances. The aim of the ICRP in setting these limits is to prevent detrimental non-stochastic effects and to keep the probability of stochastic effects at an acceptable level. To do this, the ICRP had to take a view on the level of probability of stochastic effects that might be acceptable. By examining the probability of effects on health and of the effects of accidents in ordinary life and in common occupations, ICRP decided that its recommended dose-equivalent limit to the whole body (5 mSv per annum) for critical groups would also correspond to an acceptable level of risk to members of the general public. This limit for individuals in a critical group would probably result in an average dose-equivalent to the whole population of less than 0.5 mSv, provided that the practices causing the exposure were few and caused little exposure outside the critical group (*4,21*).

The notion of an acceptable risk of ill health needs some elaboration. Trade-offs among costs, convenience, comfort and possible health risks are implicitly made by the individual in many everyday activities, such as car driving, cigarette smoking, dietary habits, air travel, or choice of occupation. Some trade-offs are also made for the individual by government bodies, for example through building codes, road safety requirements, standards for environmental protection, the regulation of drugs and food additives, standards for consumer products, and the allocation of public resources for health protection, medical research and regulatory activities. Allowable risks from energy sources fall into the category of government-imposed limits rather than individual choice.

The disposal of long-lived radioactive waste may involve the possibility of radiation exposure to future generations. Since they may not receive any direct benefit from the practices generating these wastes, some groups have argued that this exposure without benefit or consent is unethical. The impact on future generations of actions taken today is not unique to nuclear waste management. The depletion of fossil fuels will also affect future generations, as will other decisions related to land use, mineral resources, population growth, medical care and education. With regard to the health risks from nuclear waste, future generations should not be expected to face risks that we would not consider acceptable today. This objective would be achieved by ensuring that future doses are kept well within the ICRP dose limits.

The ICRP dose limits apply to uniform exposure of the whole body and to the tissues of certain organs such as the skin and eye. In considering potential exposure from the disposal of high-level radioactive waste, it will usually be necessary to consider uneven body exposure or cases where certain organs of the body receive most of the radiation dose as, for example, when water is ingested that contains radionuclides that concentrate in an organ of the body. The ICRP has recommended the use of the effective dose-equivalent for comparing doses received by individual organs with the recommended effective whole-body dose limit, and for calculating collective doses to populations for the purpose of limiting them to a reasonably achievable level (*21*).

The dose-equivalent is applied to ionizing radiation of different types, which have different capacities for affecting health per unit of absorbed energy. The effective dose-equivalent (H_E) is given by:

$$H_E = \Sigma_T W_T H_T$$

where W_T is a weighting factor representing the fraction of risk (of producing fatal cancer in the organ of the individual, or of genetic defects in the first two generations) resulting from tissue T when the whole body is irradiated uniformly, and H_T is the dose-equivalent in tissue T. The ICRP weighting factors are discussed elsewhere (*2, 4*). The use of the effective dose-equivalent allows for a systematic summing of the risk to various organs and tissues from doses of non-uniform radiation or from the intake of radionuclides. Thus, the doses received or potentially receivable in all the different pathways (external, ingestion, inhalation, through skin, etc.) from a given system of disposal may be related to a single measure of overall risk for comparison with other systems of disposal.

The weighting factors are averages; in practice, the relative risk of effects on health would vary with age and sex and probably other characteristics of the exposed individual, but ICRP considers that the average is sufficiently accurate. The use of the procedure has been criticized because it ignores the risk of non-fatal cancers and of genetic effects in generations subsequent to the second. ICRP has considered this criticism and concluded that, in general, the risk of non-fatal cancers is not significantly increased unless organs such as the skin and the thyroid, which have a low cancer fatality rate, are the only ones irradiated, when the risk might be twice that calculated by the effective dose-equivalent procedure. The extra genetic risk would be 24% at most, except in the unlikely case of the gonads receiving the dominant dose (*22*).

Application of the ICRP framework

The ICRP recommendations are made for the planned, controlled exposure of workers or members of the general public to ionizing radiation. While the exposure of workers involved in the disposal of high-level radioactive waste is therefore controlled by the principles and recommendations of the ICRP framework, the objective is to prevent any exposure of members of the general public. The risk of unplanned, accidental exposure or releases of radioactivity cannot be entirely eliminated, however, and since such exposure or releases have the potential to contribute doses as great as, if not greater than, those received in normal operations it is necessary to consider how the principles underlying the ICRP recommendations may be used to formulate an appropriate framework for the disposal of high-level radioactive waste.

There are four underlying principles or assumptions.

1. Since the average mortality rate from industrial accidents (excluding the more hazardous occupations) is of the order of 10^{-4} per person-year, a risk of this order from exposure to ionizing radiation should be acceptable as a maximum limit for occupational exposure.

2. This level of risk corresponds to about 5×10^{-3} Sv per year.

3. The average radiation worker receives about a tenth of the dose of the small group of workers who receive the highest doses. Thus the ICRP's recommended maximum occupational exposure of 0.05 Sv per year implies an average dose of 0.005 Sv per year and, therefore, 10^{-4} fatalities per person-year.

4. The ICRP's recommended effective dose of 0.005 Sv per year to individuals in critical groups of the general public similarly implies a considerably lower average dose to the whole population, depending on the size and dose-distribution of the critical group and on other factors, with a correspondingly lower fatality rate.

It must be emphasized that these figures are approximate, as was explained in the discussion of the ICRP framework, and are given only for illustration. National authorities may set authorized limits that differ from the ICRP recommendations, provided the effects do not extend beyond their own frontiers. Where there are international implications, however, international agreement will be necessary. The Working Group did not attempt to make proposals for international acceptance, but considered that there was a clear need for the appropriate international organization to do so and noted that this was under consideration by IAEA.

Irrespective of the particular figures that may be adopted internationally, it is possible to formulate a framework of principles, similar to and based on the ICRP framework, for the specific case of the disposal of high-level radioactive waste. It is based on the obvious premise that no system, however well conceived and designed, can guarantee that there will be no release of radionuclides and no exposure of the general public. At all times there will be some possibility, however remote, that this will occur.

The approach to the problem that has received most attention is the identification of all the possible events or chains of events that could conceivably lead to human exposure, and the evaluation of the probability that the event or chain of events will occur. In general, the probability will depend on time; as a simple example, the probability that an external package will fail by corrosion may increase with time. In principle, a probability of occurrence as a function of time can be assigned to any event or chain of events. With each postulated event or chain of events, there will be associated a potential exposure either of workers in the repository or of members of the general public and, based on the underlying principles set out at the beginning of this section, the probability (risk) of an effect on health may be calculated.

Thus, for every conceivable event or chain of events, two probabilities may be calculated.

1. The probability that it will occur, which is a function of time.

2. The probability that effects on health (fatalities, and non-fatal disease and genetic effects) will be associated with it.

The product of these two probabilities is the probability of effects on health occurring (as a function of time) as a result of that event or chain of events. To calculate the total probability of effects on health from all the conceivable events for the particular waste disposal system under study, the probabilities of all the conceivable events must be added up. It is not possible to do this by simple addition since the probability that one event will occur could influence that of another occurring, and some weighting factor may have to be assigned to each probability before addition. In principle, the results can be set out as a table showing the probability of effects on health at selected times after disposal, and the probability can be judged for acceptability against the principles of ICRP set out at the beginning of this chapter.

Of course, the probabilities cannot be calculated with great precision; the calculated models will be subject to many uncertainties through lack of data or knowledge of parameters. This can be taken into account in the assessment of the overall probability of radiation doses being received by assigning less weight to the more uncertain data, for example, or by assigning bounds to the values of parameters instead of single figures. It is sometimes said that, because of the considerable uncertainty about remote situations, the method cannot be reliable; this is not necessarily so because it does not follow that the probability of releases, or of an individual receiving a dose above a predetermined level, will increase as the uncertainty of the parameters increases. The uncertainty is not really a criticism of the method, but is a reflection of the limits to our knowledge, and provided the uncertainty is carried through to the final evaluation of the probability (so that its range of possible values is appreciated) it does not invalidate the method.

In some discussions on the disposal of high-level radioactive waste, criteria based solely on the consequences (effects on health) of the release of radionuclides have been used, without regard to the probability of occurrence of the release. Such criteria are inappropriate because one of the components of overall risk is ignored. Moreover, they are fundamentally unworkable as a basis for applying the ICRP recommendations because it is always possible to identify a hypothetical release mechanism, even if it has an extremely low probability of occurrence, which would lead to higher doses of radiation than those chosen as the upper limit of acceptability.

For these reasons it is not yet possible to apply the ICRP system of dose limitation to the disposal of high-level radioactive waste in a straightforward way. It is necessary to develop radiological protection criteria that embody the basic principles of keeping risks to individuals and the population at acceptable levels, and which take account of both the probability of the release occurring and the probability of harm following the event. The general form of the criteria can be derived by analogy with the ICRP system of dose limitation (*20*):

(*a*) the risks to individuals (both workers and the general public) should not exceed specified levels; and

(*b*) the total risk and impact on public health should be as low as reasonably achievable, economic and social factors being taken into account.

The risks are a combination (product) of the risk (probability) of a release and the risk (probability) associated with the consequences to health of the radiation doses.

The risk to individuals

It is generally agreed that a disposal option cannot be accepted if it entails risk to individuals (either workers or those in the critical group of the general public in future generations) which are greater than those currently considered to be acceptable. It follows that the criterion for individual risk should be satisfied over all time. In assessing or comparing the options, the risk to individuals should be calculated using realistic estimates of parameter values including their ranges of error; this will ensure that compliance with the criterion for individual risk has been demonstrated. The criterion for individual risk will then provide a mechanism for screening disposal options and identifying critical parameters and assumptions at an early stage in the study of their feasibility, when there is still time to obtain more data and make more accurate estimates.

In order to apply the criterion it is necessary to combine the predictions of the probability of occurrence and of its consequences to obtain a measure of overall risk. As previously described the probabilities, modified by weighting factors, are added together. Less weight may be given to the probability of doses from low probability events compared with doses from high probability events. There is ample room for subjective judgement of the relative importance of the possible events in the choice of these weighting factors.

The Working Group noted that certain reservations have been expressed concerning the ICRP dose limits: on the one hand that they may be too low, because of the assumption that there are no threshold and linear relationships between dose and effect, and on the other hand that they may be too high, because of the neglect of some cancers and genetic consequences in the derivation. On the whole it seems more likely that they are conservative. There are also other considerations of a non-technical nature that may have to be taken into account in making these decisions and which might influence the levels specified nationally and internationally. The Working Group preferred to leave the matter open without prejudice, but emphasized the importance of future work in this area.

The total risk

The criterion for total risk, as formulated for this purpose on the basis of ICRP principles, requires that the disposal method should be optimized. This implies:

(*a*) that the possible alternative methods of disposal should be compared and that the alternative selected should be the one that minimizes the total cost; and

(*b*) that the selected method should be modified to reduce the total risk until further expenditure cannot be justified by the reduction achieved.

In practice these two steps may not be separate, and several methods of disposal may survive to the second stage for final comparison.

The criterion for total risk does not specify a limit, although in fact the limit for individuals, which is applied to the mean dose of the critical group, would limit the total risk and would apply over all time. A practical difficulty in making the calculation is that the population postulated as being exposed to radiation from the presumed event may be infinite, being all subsequent generations, and that the dose never actually vanishes because, although radioactivity decays, it never becomes zero. The Working Group took the view that the total risk should be seen in the context of the natural risks from exposure to radiation already present, such as that from ore bodies, and that the predicted dose to populations from the disposal of high-level radioactive waste could be ignored when it is a small fraction of the natural background. The Working Group was also generally unwilling to attach much importance to rather uncertain predictions of low doses to large numbers of individuals many years in the future, even though the calculated collective doses might be large.

Discussion

Although the Working Group did not formulate these views into precise recommendations, they considered that two suggestions deserved further consideration. One was that once the potential for harm of a high-level radioactive waste repository had dropped below that of naturally occurring ore bodies, taking into account the pathways back to man, the need for concern would be much reduced and need be no greater than that now accorded those ore bodies. In practice that would probably mean ignoring further contributions to the total risk. The other suggestion was that when the mean dose to the critical group, as predicted from the models, dropped below a specified level (probably in the range 10^{-6}–10^{-4} Sv per year) then further doses need no longer be considered in the calculation of total risk.

The risks associated with the disposal of high-level radioactive waste extend over extremely long periods of time because many of the radionuclides concerned are very long-lived. The uncertainties in the calculation of the risk clearly increase with time after disposal. In demonstrating compliance with the first criterion, relating to individual risk, these uncertainties can be taken into account by the use of sufficiently conservative or pessimistic assumptions and parameter values. On the other hand, as previously pointed out, the calculations required for complying with the second criterion for total risk should be as realistic as possible, since otherwise the comparison of options and the optimization process will be invalidated. Even so, for estimates of the total risk to populations (which require a projection of numbers and distribution over many centuries) and of the cost of the risk (which will depend on the social attitudes of the populations over this time) efforts to quantify the uncertainties are likely to lead to a range of values too broad to be useful as a basis for comparison and optimization of disposal options. This can be resolved by weighting the contributions to total risk according to how long after disposal they occur, thus avoiding undue emphasis on long-term risks that cannot now be assessed realistically.

Although the calculation can be resolved in a mathematically satisfactory way, it should be borne in mind that the choice of weighting factor amounts to a quantification of a subjective assessment of the importance of long-term effects. It is a role that the public health official, as adviser to government or local health authorities, should have some share in by being closely involved in the calculations, making sure that he is quite familiar with the weighting factors chosen so that he may accurately reflect their importance in his advice.

Mode of action

It is possible at this point to set out the steps in the process necessary for conspicuous compliance with the two basic principles or criteria that have been formulated on p. 27.

1. Identify all practicable options. In this process of identification it will be found that some have been developed more fully than others and some may have to be rejected for lack of sufficient information. If a rejected option appears to be promising it may be possible at this stage, depending on the time available, to initiate studies to provide more data and, if the results justify it, to reinstate the option.

2. Determine whether each option meets the ICRP dose limits (or such other limits as may be specified) for all individuals over all time. Reject the options that do not meet this criterion.

3. Determine the monetary cost of each remaining option.

4. Determine the collective population dose associated with each remaining option.

5. Eliminate the options that have both higher cost and higher collective dose than other options.

If only one option survives at this stage, it will be chosen in accordance with the second criterion. If not there are two further steps.

6. Multiply the collective dose by the assumed monetary value of the reduction in total risk, i.e. the cost per man-Sv.

7. Select the option that gives the smallest total cost.

One of the great advantages for the public health official of a methodological approach of this nature is that it requires that the arguments for selecting the option be set out in a systematic order, so that the gaps, assumptions and uncertainties are clearly brought out. The public health official can then take part in the decision-making process, contributing his own views to the assessment when subjective judgements have to be made. Finally, when the selected option is to be approved or publicly discussed prior to approval, he will be able to describe the selection process and the assumptions clearly so that political decisions can be made properly. The final political judgement may for quite proper reasons differ from the technical judgement of the best option, but the reasons for selecting the latter at least will have been clearly set out and understood.

4

Disposal options

The only process now in industrial operation for the immobilization of high-level radioactive liquid waste, the French AVM process, produces a block of borosilicate glass weighing about 360 kg, cast into a stainless steel canister 0.5 m in diameter and 1 m high. The canister is sealed with a welded lid, decontaminated, and stored in an air-cooled vault consisting of cylindrical holes in a concrete base with steel caps (*14*). If other immobilization processes are successfully brought into operation on an industrial scale, their waste products could also be stored in this way. Although storage of conditioned high-level radioactive waste for longer than a few decades is technically feasible, it is not generally considered acceptable and the problem of disposal must be pursued. While it is being worked out, buffer storage of the product is required (*23*).

Any storage/disposal option will consist of a number of unit operations of which the initial steps will be in common:

- the buffer storage of high-level radioactive liquid waste as it is produced
- the transfer to longer-term liquid storage to permit decay
- the decay storage of liquid waste
- the transfer to an immobilization plant
- the buffer storage of liquid waste at the immobilization plant
- immobilization (consisting of two steps in the AVM process)
- the sealing of the canister
- the decontamination of the canister
- the transport to the store
- storage.

Stainless steel is chosen as the canister material because it resists the chemical and radiation damage of the casting operation and subsequently of the hot, intensely radioactive waste in store. It may be necessary to provide an additional package for the waste, perhaps at a later date when substantial decay has occurred, in order to improve the confinement during the long period in the final storage/disposal.

At first sight the choice between long-term storage and disposal seems to be in favour of the former, since it avoids further handling, transport and field operations; on the other hand, over the long period envisaged, periodic rebuilding of the store might be necessary and the possibility of the release of waste, as a result of a deterioration in storage, has to be considered. In fact, the requirements for the waste in store could be as demanding as for the waste in a repository. Moreover, if adequate surveillance and preservation of records over the long storage time cannot be assured — and the time is longer than most civilizations have lasted without upheaval — planned disposal in a more remote place may actually be preferable by the criteria developed in Chapter 3.

In fact the choice is not simply between storage and disposal. Since buffer storage is an integral part of any disposal option, there is a wide range of possible disposal systems, with different periods of storage for the liquid and solid storage unit operations in the systems, and these parameters, in addition to the method of disposal, have to be taken into account in evaluating the disposal system. It is the system as a whole, and not just the disposal option, which has to be identified in the first step of the outline process of evaluation described at the end of Chapter 3.

Geological disposal

The most advanced concept for the disposal of high-level radioactive waste at the moment is isolation in mined geological repositories (*24*). Several geological media are being investigated at both national and international level for their potential to confine the waste over very long periods. This natural system would provide, in addition to the barriers engineered into and around the waste itself (solidification, packaging, surrounding sorptive material), multiple barriers capable of preventing or retarding the migration of radionuclides from the repository to the biosphere.

The natural system of barriers comprises the repository host rock, the surrounding geological formations and the hydrogeological environment. There are two broad objectives: to minimize the probability that circulating groundwater will come into contact with the waste package, and to minimize the migration of any radionuclide that may be released. The criteria for site selection (*25*) are related to the host rock, the environment of the rock, the potential for breaches of the repository, and the construction of the repository. Though these four general groups of criteria are discussed here separately for ease of presentation, there is some overlap; for example, hydrological conditions are related to rock-type and construction problems.

The host rock should be at a depth such that any reasonable or likely natural processes at the surface do not unacceptably affect the performance of the repository. It should be large enough in all directions to accommodate repository workings and to ensure that the construction and operation of the repository do not unacceptably affect its performance.

The thermal properties of the host rock determine its capacity to absorb and dissipate the thermal energy emitted by the radioactive waste. The absorbed energy can alter pre-existing mechanical and chemical equilibria, and thermal expansion can produce stresses and deformation which may cause fracturing and creep. The mechanical properties of the rock determine the sort of deformation that may be induced by heat and by the construction of the repository. Salt and shale exhibit creep deformation and so have the ability to deform in such a way as to continually seal the potential pathways for groundwater flow. On the other hand, a more rigid rock like granite provides more stable mine openings, and tunnels and pillars more resistant to failure from thermally induced stresses.

The host rock may act as a physical barrier to water movement and as a sorbing medium capable of removing radionuclides dissolved in groundwater. Its efficiency as a physical barrier depends on a variety of factors, including: groundwater flow rates; the fracture geometry and characteristics, and its porosity; the temperature and pressure gradients in the vicinity of the repository; and the specific surface area of rock and fracture-filling materials exposed to circulating groundwater. As water moves through the rock, radionuclides may be removed by a variety of processes, including precipitation, ion exchange, surface adsorption and solid solution formation, which fix them temporarily or permanently to the rock. These processes greatly reduce the actual rate of movement of most radionuclides and keep it well below the theoretical maximum determined by the groundwater flow. In these respects, salt is distinctly inferior to granite and sedimentary formations. In some geological settings (evaporite formations, for example) the capacity of groundwater to dissolve the host rock must be considered.

The transport of radionuclides away from the repository by moving groundwater is the most likely mechanism by which they could migrate to the biosphere. An understanding of the hydrogeological characteristics of the host rock and its environment is essential for predicting the directions and rates of movement of radionuclides. The pertinent characteristics include: the locations and dimensions of water-bearing strata; the existence of aquifers; the hydraulic gradient; the porosity and permeability of the rock surrounding the repository; the rates and locations of groundwater discharge and recharge; the length and direction of potential flow paths from the repository to the biosphere and the sorption of radionuclides in these paths; and groundwater ages near the repository.

Tectonic processes, climatic changes (which may particularly affect hydrological conditions), ground erosion, and other similar long-term effects have to be considered. Potentially disruptive tectonic effects could result from faulting, seismic activity, volcanic activity, uplift, subsidence, and alterations in natural stress conditions. The possibility of ground erosion should be of some concern near major rivers and steep escarpments.

Finally, it would be prudent to ensure that the siting of the repository does not preclude the extraction of significant quantities of economically useful minerals now, or in the future, while such deposits in the vicinity of the repository should not be so near as to present a significant risk of inadvertent breaching of the repository system by future drilling or mining.

In the preliminary screening for possible types of repository site, a subjective analysis of these considerations has been made, including some weighting of the different issues. Certain geological formations appear to satisfy several of the requirements, especially the important one of geological stability. The host rocks that are now receiving attention include salt deposits, hard rocks such as granite and basalt, and sedimentary formations. The Commission of the European Communities has an integrated research programme with full sharing of the results (*26*); in Sweden, a full feasibility study of the disposal of spent nuclear fuel has been made (*27*); and there are active Canadian and United States programmes. The results of this research are shared under bilateral agreements.

Although the general properties and behaviour of the three chosen rock formations are fairly well known, their expected behaviour has to be checked by measurements *in situ*. It is only in this way that representative values of the important parameters such as stress distribution and temperature can be obtained. Much of the present work is directed to this end.

The study of groundwater *in situ* is of major importance because, apart from direct access by man, this is the only reasonably likely natural route by which the radionuclides could return to man's environment. The identification of faults in the rock formation and their nature, and the construction of realistic models for groundwater flow are important aims of these studies. While it may be expected that cationic forms of radionuclides will, for the most part, be readily adsorbed on rocks, especially clays, the behaviour of anionic forms, such as those of the transuranium elements (especially neptunium) and technecium is less well understood and needs detailed research (*28*).

The second important factor is the temperature to which the underground disposal facility is subjected. Various feasibility studies have set limits of anything from 100 °C to 200 °C for the permitted temperature of the surrounding rock. It is possible to stay within this limit by suitable design of the repository and spacing of the waste elements, but more studies are needed to determine how critical for the cost and stability of the repository this limit may be.

Salt formations

Salt deposits suitable for repositories occur in stratiform masses (bedded salts) and in salt domes; the latter are usually more pure and more homogeneous. Some of the formations now under consideration are known to be millions of years old, testifying to their isolation from water and to their stability. Undisturbed formations are essentially impermeable, their water content being immobile. The high thermal conductivity gives good heat dissipation but there is some loss of mechanical strength as the temperature increases. Its plasticity, which heals cracks and will seal in the waste as the salt backfill consolidates, is an advantage for isolating the waste, even though it may lead to some difficulties in stabilizing the tunnel openings; the extensive knowledge available of mining in this material suggests that the difficulties can be overcome.

Extensive work on salt formations has been done in the United States (*29–31*). It revealed one possible path by which the waste might come into contact with brine. Natural salt may contain some brine which can migrate towards the heat source, but the volume of the brine inclusions is small relative to that of the waste and presents only a minor difficulty.

In the Federal Republic of Germany work is continuing into the possibility of using Asse halite, which has an extremely low water content. Experiments *in situ* have confirmed laboratory tests of mechanical strength, and show that the borehole containing the waste canisters would soon be sealed by creep of the salt. Stress measurements are being made. The possible results of the flooding of a repository have been studied by taking measurements in the flooded shafts of former salt mines in the Federal Republic. They showed that the interface between salt water and fresh water is quite distinct; there is evidently no rapid movement across this interface (*32*).

Studies have also been made in the Netherlands in collaboration with the German work. The feasibility of dry-drilling long boreholes in salt has been demonstrated in the Asse mine. The possible consequences of the flooding of a repository have been determined by modelling; in all the cases studied, the release model gave concentrations of radionuclides in drinking-water below guideline levels. Though the model may be crude, owing to insufficient data in this early stage of the work, the result shows that even such an accident would be by no means catastrophic (*32*).

The conclusion from the work so far done in these countries is that disposal in suitable salt formations is feasible.

Crystalline rocks

Work on this option for the disposal of high-level radioactive waste is being done in Canada, France, Sweden, the United Kingdom, and elsewhere. The work at the Stripa Mine in Sweden, originally a bilateral effort with the United States, is being extended under the sponsorship of the OECD Nuclear Energy Agency with the financial support and technical participation of Canada and Switzerland.

The crystalline rock attracting most interest is granite. Granites are dense matrices of equigranular coarse grains and are of low porosity, with little or no water content, and of low intergranular permeability. Having been formed originally at high temperatures, they are basically unaffected by heat, though the thermal expansion of particular minerals may be sufficient to cause (or close) fractures and surface heave. A repository in a massive granite formation might be expected to be well isolated from flowing groundwater and access by man, provided a nonfractured mass of suitable extent is chosen.

Laboratory work has been directed towards determining the physical and sorptive properties of the rock. Measurements *in situ* have confirmed the calculations of temperature and stress distribution based on the laboratory work. Cores provide information on rock quality and discontinuities (*33*).

Sedimentary formations

These consist of sediments deposited in basins, usually of considerable extent. They are of low porosity and possess high sorptive capacity for cations. The generic term includes argillaceous rocks, ranging from plastic clays and marls to consolidated mudstones and shales and the metamorphosed schists and slates, and it is these that have received most attention.

The clays are self-healing for cracks and fractures owing to their plasticity, but are sensitive to heat and gamma radiation owing to the presence of interstitial water. They are easy to work but the structural support of tunnels and openings is required. Thus, clay can provide both a physical and a chemical (sorptive) barrier and there would be no need for a packing of extra sorptive barrier material around the canisters in the repository.

It has been concluded from preliminary laboratory work in Belgium and Italy (*34*) that compact clay formations at a depth of 200 m and more than 50 m thick can be considered as potential repository sites, but the effect of heat and radiation (radiolysis of water) must be carefully evaluated at each site in order to determine its suitability. An underground laboratory is to be built at a depth of 220 m on the nuclear site at Mol in Belgium, in order to carry the work further.

Conceptual design of repositories in geological formations

Conceptual designs have been formulated in Belgium, Canada, France, the Federal Republic of Germany, the Netherlands, Sweden, Switzerland, the United Kingdom and the United States (*35*).

The first step may be to provide storage for many years, since the heat emitted decreases with a half-life of about 100 years; periods of 10–100 years are being considered.

The designs are commonly based on the assumption that the waste in the steel canisters will be in the form of glass, but that the size of the canisters and the loading of fission products can be adjusted within limits to accommodate specific conditions for handling, transport and cooling. There has also been some discussion about the design of the canisters; for example whether to provide an overpack, or instead a thick canister of relatively low resistance to corrosion, or a thin one of high resistance. The probability that radionuclides might be released from the waste via groundwater could be reduced by additional packing of the canisters — lead and titanium have been considered (*27*) — and the canisters could be surrounded with materials of high sorptive capacity, such as bentonite.

The heat generated by the stored waste will be dissipated into the rock mass. The likely temperatures can be predicted with some confidence, but the effect on the rock is not so well understood and is still being studied. At present it is better understood in salt than in granite or clay, but information is being obtained for these two rocks from the work previously outlined. Rock temperatures in the range 100–200 °C have been envisaged as the maximum permissible in the conceptual designs.

The repository is supposed to be 250–1000 m below the surface but, in clay mining, difficulties can be encountered if the depth is much greater than 250 m. Practically all the designs envisage that the canisters will be placed in holes drilled in the floor of the repository. The drilling of blind holes of large diameter underground requires further development, but there is little doubt that the problems can be overcome.

The cost of constructing a repository is dependent on all these factors and has not yet been calculated in detail. The investigations now being undertaken will provide additional data from which more accurate estimates may be expected, but it is already clear that the cost of repository construction and operation will be only a small fraction, of the order of 1%, of the whole cost of nuclear power. It is possible that these first conceptual designs may be conservative and that less expensive options may be justified by the additional data.

No evidence has emerged to suggest that the radiological consequences will be unacceptable, but this will have to be demonstrated by the specific models developed from the conceptual designs and by the site-specific studies. At present, the models are crude and are being used to establish what are the important and critical data, so that investigations can be directed towards obtaining them. As the data are obtained, the models can be refined. The process is iterative, with the models requiring data and the data modifying the models.

In the end a model will be developed that will apply to the whole system of disposal and will be designed for the optimization process. The evaluation of the steps in the system will be fairly straightforward for the initial unit operations, such as handling and transport, since these are processes to which the ICRP recommendations apply directly. Transport is governed by the well established IAEA Transport Regulations (*36*). It is the steps subsequent to abandonment which will be less certain; their evaluation will be based on models that use data obtained under experimental conditions. These conditions may have to be extrapolated over long periods of time, resulting in conditions that cannot be exactly reproduced experimentally. It is not possible, for example, to predict exactly what a canister of vitrified waste will be like 1000 years hence.

Environmental modelling has normally used one of two approaches. In each, the flow of radionuclides through the environment will be separated into conceptual compartments — in a particular case perhaps defined by the barriers of the canister, the overpack, the absorbent packing, and the groundwater in the repository, in the neighbouring rock and in remoter rocks, as well as by plants, animals and so on through the relevant food chains. In the method using concentration factors, the parameters in the model are the ratios of the steady state concentrations (concentration factors) in adjacent conceptual compartments. In the method using systems analysis more emphasis is placed on the dynamic conditions before equilibrium is reached, which may well be more realistic in this case since the transport of the radionuclides is slow even on the appropriate time-scale. A set of partial differential equations is formulated to describe the change in the system with time, analogous to those formulated for physiological studies.

The accuracy of the data and the precision required in the prediction may not justify such elaborate approaches and there appears to be a movement away from comprehensive models based on fundamental physico-chemical and biological principles towards simpler, experimentally based regression models. The uncertainty of the safety evaluations, however, and discussions of what are appropriate models for the safety evaluations, should not be allowed to obscure the fundamental safety of the proposals for the disposal of high-level radioactive waste which, in a less sophisticated age not so many years ago, might have been accepted without more ado. The waste is incorporated in glass, enclosed in corrosion-resistant material, surrounded by absorptive material, placed in a deep hole in a stable, impermeable geological formation, and after about 1000 years the waste will be about as active as naturally occurring radioactive ores, since, despite all the uncertainties, it is difficult to envisage the dispersal of a significant amount of radionuclides in that time.

Ocean disposal

In principle, the same methods may be used to evaluate other disposal options, but these have not received the same detailed consideration and field work as geological disposal. Probably the most promising option, or rather group of options, relates to ocean disposal and includes five possibilities.

1. Engineered emplacement into deep ocean sediments (under the sea bed).
2. On the ocean floor (on the sea bed).
3. Subduction zone.
4. Oceanic fracture zone.
5. Major sedimentation fans.

Engineered emplacement

This may be considered as disposal in a geological formation, that forming the sea bed. A programme administered by Sandia Laboratories has been investigating this option in the United States since the early 1970s (*37*); more recently, the OECD Nuclear Energy Agency has also been coordinating and encouraging studies of it. Although very substantial points of uncertainty remain, nothing has yet emerged from the studies to refute the view that deep ocean sediments of several different types or origins may serve as extremely effective barriers in a multibarrier system for isolating high-level radioactive waste and delaying re-entry into the hydrosphere by 10^5–10^6 years. Some of the points of uncertainty are likely to be cleared up by experiments now planned or under way.

This option seems to offer a number of advantages.

1. The very large area of sediments available.

2. The uniformity of the properties of the sediments over large areas, which enables model parameter values to be established with some precision from a small number of sediment cores coupled with geophysical surveys.

3. In many cases the established isolation of the sediments from the effects of weather and climate. In the North Pacific, for example, the glacial periods can be shown to have had no effect on sediments or sedimentation over periods up to 70 million years long.

4. The availability of large areas free of seismic or tectonic activity and where the loci of volcanic activity can be predicted quite accurately.

5. Low porosity and high sorptive capacity for most of the relevant radionuclides.

6. A self-healing capacity in respect of the intrusion of waste packages or other disruption in the case of non-lithic soft sediments.

7. The general poverty of deep ocean areas in resources exploitable by man.

These advantages may be compared with the discussion of the similar properties of the rocks now under investigation, presented in Chapter 3. It is perhaps not widely realized that predictions about the properties and behaviour of oceanic sediments, either over distance or over time, are more accurate than for most rocks of the dry surface of the earth.

However, this option raises some political issues which, though not properly part of a technical assessment, cause real practical difficulties. In the end, the judgement of the acceptability of an option has to be based on the estimation of the risk to health and the uncertainty of the estimate. In the case of disposal on land, the judgement can be made by a national authority in consultation, if necessary, with its neighbours, but in the case of ocean disposal many nations will have to be involved in the judgement, and naturally those that have no interest in the disposal of high-level radioactive waste will be more severe in their judgement than those that do. They will be less inclined to risk interference with the sea's natural resources, even to the extent of outright opposition to any use of the oceans for waste disposal.

It is not part of our study to express any opinions on this difficult international issue, but we have to recognize that it may limit the potential of this option. We recommend that, through the appropriate international bodies, consideration be given to formulating an agreed level of risk as a basis for this option.

On the ocean floor

It has been proposed that immobilized waste be placed in appropriate containers of expected long durability on the floor of the deep ocean. If the deposit were made in stable sediment, an extra barrier would be present to retard the movement of radionuclides from the place of deposit, unlike deposition on a hard rock ocean floor. The engineered barriers in this general option would be the form of the waste and the waste container. With the present state of knowledge of ocean currents, and removal and transport processes in the ocean, it is virtually impossible to develop realistic models for estimating the possible doses to man. More data in these areas are needed for a realistic appreciation of this option. Under the terms of the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, high-level radioactive waste is unsuitable for sea dumping, based on the IAEA's definition and recommendations (*38*).

Subduction zone

It is an attractive thought that immobilized waste, in appropriate containers, placed in the area where the earth's crust under the ocean is moving downwards into the earth's interior, would be carried with it to melt and disappear, perhaps for ever, or at any rate for hundreds of millions of years. At present we are unable to identify with certainty the ocean bed areas that will sink uninterruptedly, in contrast with those that will be affected by local tectonic or volcanic activity and returned directly to the earth's surface.

Ocean fracture zone

These are often areas with high rates of sediment accumulation and low tectonic activity, which offer attractive possibilities. Unfortunately, they have been shown to experience sporadic scouring by turbid current flows. These leave thick sediment deposits behind but they are unpredictable and could be expected to disturb any waste emplacements in their path.

Major sedimentation fans

These are the very soft, very rapidly accumulating deposits off the mouths of major rivers such as the Mississippi, the Ganges and the Nile. These sedimentation fans are strongly affected by climatic changes and by man's use of the river and are also liable to move unpredictably by slumping or creeping of the soft sedimentary material.

Other options

A number of other ideas have been considered for the disposal of high-level radioactive waste but they are generally of little continuing interest compared with the geological and under-sea-bed approaches, and none has been developed to the stage where it can be properly costed and optimized (*30,39*). They will be briefly described here, and some of their more important advantages and disadvantages mentioned.

Projection into space

Several space disposal ideas have been advanced. The currently favoured one entails putting the partitioned actinides into a circular solar orbit, about halfway between Earth and Venus, which is calculated to be stable for at least a million years and not to intersect the orbit of either planet. The waste might be put into earth orbit by the Space Shuttle and subsequently propelled by rocket into solar orbit.

This option would offer the opportunity of effecting disposal from the earth. On the other hand, accidents during launching and orbital transfer, which might return the waste to earth intact or as an uncontrolled dispersal, are not improbable, at any rate in this early stage of the technology.

An analysis of the cost and the consequences of an accident has not been made, and this option is little more than a suggestion.

Transmutation

Almost all of the fission products in high-level radioactive waste decay to negligible levels within 1000 years, after which time the waste activity is attributable to the actinides. The idea of transmutation as a disposal option entails the conversion of the actinides into fission products by neutron bombardment. This could be accomplished in the neutron field of a nuclear power reactor, with the energy released in this fission process added to the output of the reactor. With this option the risk from the waste disposal might be limited to less than 1000 years. Since the transmutation would not be complete, subsequent reprocessing of the actinides would be required and initially, of course, it would be necessary to separate the actinides from the waste (partition).

The idea appears to be technically feasible, though it is doubtful whether the chemical separations required could be carried out routinely under industrial conditions and considerable development would be needed. The scheme would not be unduly expensive but would probably not be cost-effective. The long-term radiological benefits would be limited and might well be outweighed by the short-term detriment arising from the partitioning and separation processes (*40*).

Emplacement in glaciers or ice sheets

Three types of proposal have been made for disposal in ice sheets: melt-down, anchored and surface.

The melt-down concept would entail placing each waste canister in a shallow hole, preferably near the centre of the ice sheet, and leaving it to melt its way down to the bottom of the ice sheet by the heat of its own radioactive decay. It is calculated that a canister would take 5–10 years to reach the bottom of an ice sheet 3000 m thick.

The concept of anchored emplacement would allow retrievability of the canister for up to several hundred years, during which time it could properly be regarded as storage. It is envisaged that the waste canister would be placed in a pre-drilled hole and would melt down until its descent was stopped by an anchored cable 200–500 m long attached to it. New snow would gradually cover the anchor plates and the entire system would gradually descend into the ice sheet. It is calculated that it would reach the bedrock at 3000 m in about 30 000 years, by which time the decay heat would be negligible. The waste and the anchors would tend to follow the ice flow pattern during the descent.

In surface storage, a storage facility would be supported by jack-up piles or piers resting on load-bearing plates within the ice. The waste canisters would be placed in cubicles inside the facility and be air-cooled by natural draught. Initially, retrievability would be possible, but eventually, when the limit of the support is reached, the entire facility would slowly melt into the ice sheet, perhaps after a few hundred years.

Although disposal into remote ice sheets may appear to be attractive at first sight, there is the possibility that the waste would reappear in the environment and that changes would be triggered in the ice sheet which could have widespread consequences. A great deal of research would be needed to predict future ice movements, accumulation (or depletion) rates of the ice sheet, sub-surface water flow rates and trigger mechanisms. A major uncertainty, of course, is the long-term global weather patterns affecting the stability of the ice sheets and the level of the seas. These options are not currently being pursued further.

Reverse well

For the sake of completeness, two methods that have been used for the disposal of low- and medium-level radioactive waste and which have been suggested for high-level radioactive waste should be mentioned, although the concept of the direct disposal into geological formations of high-level radioactive liquid waste on which they are based has come in for strong criticism and they remain no more than suggestions.

In the first, the acidic waste would be pumped into porous or fractured strata more than 1000 m deep that are suitably isolated by overlying, relatively impervious strata. The waste would remain liquid, dispersing, diffusing and reacting with the environment. The possibility of the return of certain radionuclides to the biosphere and the possibility of the reconcentration of plutonium, with the remote possibility of criticality, would have to be evaluated.

The second method is waste-grout injection into prefractured shale. The liquid waste would be mixed with cement and clay, injected into suitable shale formations, probably at a depth of 300–500 m, and allowed to solidify in a set of thin solid disks.

Future developments

None of these options, apart from disposal into geological formations, has been developed to the stage where routine operation can be considered a practicable proposition, and even the geological option needs further development. The demonstration of this option as a successful technical operation is now confidently expected, and some extensions or alternatives to the straightforward concept of the disposal of immobilized, canistered waste in engineered structures have been suggested.

Deep hole

The canistered waste would be stacked in a drilled hole 3000–5000 m deep, which would be sealed after filling. The surrounding rock would be relied on to isolate the waste and hence the depth would have to be sufficient to ensure that re-entry into the biosphere is adequately retarded. At such depths climatic or surface changes are unlikely to affect the waste.

Island

In this alternative, waste would be placed within deep, stable, geological formations beneath an island, which would be used for port facilities and access terminals and would provide a remote location with possibly advantageous hydrogeological conditions. This method could provide an extra barrier between the waste and the biosphere, as in the under-sea-bed option; the primary barrier would be the geological formation and the extra barrier the sea, depending on the hydrogeological system of the island. Dedication of a whole island to the disposal would ease surveillance for breach of the repository.

The stability of the island in the long term will depend on the geological setting. Volcanic or seismic activity and erosion must be evaluated as processes that could result in the exposure of the contents of the repository to the biosphere. The consequences of relatively slow, gross geological changes, affecting the climate or the sea level, would have to be evaluated.

Molten rock

This idea entails the placing of waste in deep holes or cavities in a configuration where the rate of heat dissipation is slow and the resulting temperature is sufficient to melt the surrounding rock. The molten rock would then dissolve or incorporate the waste. In one proposal, high-level radioactive liquid waste would be placed directly in a cavity in deep silicate rock of low permeability. In this method, in addition to the normal considerations of geological disposal, the possible release of potentially volatile radioactive species during the rock-melting period would have to be considered (*41*).

In theory, following the ICRP principles as presented in this report, all the options should be considered and evaluated, but in practice it is not possible to make the considerable effort needed for a detailed evaluation of every proposed option, and a preliminary choice is made on the basis of general considerations of radiological safety and cost. The final options then have to be more closely evaluated by doing the appropriate work to determine the parameters that affect the risk.

5

Responsibilities of international organizations

The disposal of high-level radioactive waste has international implications. The need for the isolation of some radionuclides in this waste for longer than governments and political boundaries have remained stable in the past, and the potential for the contamination of the oceans and the atmosphere, both require a set of internationally acceptable and accepted disposal methods based on internationally agreed health objectives and standards. Furthermore, some proposed methods of disposal (such as on or under the sea bed, in ice sheets, or in space) would also require international agreements or conventions. It is essential, therefore, that international organizations take an active role in ensuring that public health and safety and environmental values are protected.

IAEA, WHO, the OECD Nuclear Energy Agency, the Commission of the European Communities, and the Council for Mutual Economic Assistance are all active in this area. Their role to date has been primarily to foster the exchange of scientific and technical information. They have sponsored international working groups, published technical documents, and acted as brokers for the exchange of information among member countries. In addition, there are a number of bilateral and multilateral agreements between and among specific countries for the exchange of information. In some cases (such as the cooperative research programme at Stripa in Sweden), work is being sponsored jointly by several countries. Consideration has also been given by the IAEA to the regional siting of reprocessing plants and waste disposal sites.

International organizations should continue to function actively in the following areas:

(*a*) gathering, reviewing and disseminating technical and scientific information on present practices and trends, in a form suitable for use by all countries;

(*b*) encouraging and sponsoring research and the development of data and technology in selected areas;

(*c*) conducting and participating in studies on waste disposal in the context of regional or international planning;

(*d*) providing technical assistance, advice and training to regulatory authorities in individual countries on request;

(*e*) developing internationally acceptable guidelines, standards and codes of practice for use by the appropriate national institutions and governmental authorities; and

(*f*) discharging their responsibilities under any relevant international conventions that may be adopted, such as the responsibility of the IAEA for defining high-level radioactive waste as unsuitable for ocean dumping under the London Convention.

In 1978 the IAEA established a Technical Committee on Regulatory Aspects of Underground Disposal of Radioactive Waste, which met in London in September of that year. The principal objectives of the meeting, attended by representatives of 17 countries, were to exchange information, discuss regulatory matters of common concern, and prepare a guide on regulatory procedures for the deep geological disposal of high-level radioactive waste. Based on its deliberations, a document (*42*) was issued recently by the IAEA, which presents guidelines for the development of regulatory procedures. Although it is specifically addressed to disposal in deep geological formations, its general guidelines for the responsibilities and activities of national regulatory bodies are appropriate to the disposal of high-level radioactive waste by any means.

The Working Group endorsed these guidelines, which are based on the following considerations. The disposal of high-level radioactive waste should be regulated by governments in order to achieve and maintain appropriately safe conditions at present and for as long as may be necessary in the future. In countries where the government also undertakes the nuclear activities by which the waste is produced, the two activities of generating nuclear energy and regulating waste disposal should be effectively separate, in order that the restrictions required by the latter shall in no way be modified by the former. The aspects which the regulating authority within the government should take into account include: health and safety; the environment; land- and resource-use planning; the effects of repository construction (mining); waste processing; waste transport; and legal liability.

Because some of these aspects are unique to repositories, existing licensing procedures and conditions may need to be modified or extended to achieve proper control of the activity. Since there is little experience available regarding the disposal of high-level radioactive waste in repositories, the procedures and conditions may have to be altered as experience grows. The public should be adequately informed about these provisions, and the changes and the technical basis for them should be fully and openly discussed.

A basis for the open discussion and development of the technology in this field is provided by the IAEA in its programme on the underground disposal of radioactive waste, which began in 1977. The objective of the programme is to publish a series of technical reports and safety guidelines in five major areas.

1. Generic activities including regulatory activities, safety assessments, basic guidance and criteria.

2. The investigation and selection of repository sites.

3. Criteria for the acceptance of waste in repositories.

4. The design and construction of repositories.

5. The operation, shut-down and surveillance of repositories.

Some of the documents already published in this programme have been referred to in this report (*24,25,42*). A fuller discussion of the technical bases of regulation has also been published (*43*).

The duties and responsibilities of the government agency should be clearly identified. Its functions will include:

(*a*) developing regulations or guidance on the criteria for selecting sites, designing, constructing, commissioning, operating and sealing repositories;

(*b*) prescribing the information to be supplied by the implementing organization at each stage, and reviewing and assessing it;

(*c*) issuing licences, authorizations and directions in accordance with national policy;

(*d*) inspecting sites and enforcing conditions;

(*e*) keeping licences and conditions under review;

(*f*) if necessary, initiating its own investigations and research; and

(*g*) maintaining contact with regulatory bodies in other countries and with international organizations.

The control of high-level radioactive waste disposal is not exclusively a matter for the implementing and regulatory bodies, but may also involve decisions of a political nature that may affect the regulatory process. At all stages, consideration should be given to the involvement of all parties with a legitimate concern in the implementation. This is particularly important in the case of local inhabitants who may be affected and especially so if they are nationals of a neighbouring country. The methods by which they are fully informed and their views ascertained and discussed should be developed at the outset and may require bilateral agreements with neighbouring countries. It should be demonstrated publicly that local views have been adequately considered in formulating the regulations.

REFERENCES

1. *Health implications of nuclear power production.* Copenhagen, WHO Regional Office for Europe, 1978 (WHO Regional Publications, European Series, No. 3).
2. *Nuclear power: health implications of transuranium elements.* Copenhagen, WHO Regional Office for Europe, 1982 (WHO Regional Publications, European Series, No. 11).
3. **Williams, L.** The world energy situation and the response of the European Community. *Journal of the Institution of Nuclear Engineers,* **21**(1): 3 (1980).
4. **International Commission on Radiological Protection.** Recommendations of the ICRP. *Annals of the ICRP,* **1**(3), 1977 (ICRP Publication 26).
5. **International Commission on Radiological Protection.** Limits for intakes of radionuclides by workers. *Annals of the ICRP,* **2**(3/4), 1979 (ICRP Publication 30).
6. *The effects on populations of exposure to low levels of ionizing radiation.* Washington, DC, US National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation, 1980.
7. **International Nuclear Fuel Cycle Evaluation.** *Summary and overview. Status of technologies related to radioactive waste management and disposal.* Vienna, IAEA, 1979.
8. **United States.** *Report of the President's Commission on the accident at Three Mile Island.* Oxford, Pergamon Press, 1980.
9. *Radioactive waste management glossary.* Vienna, IAEA, 1982 (IAEA-TECDOC-264).
10. **Clelland, D.W. & Corbet, A.D.W.** The management of high-level liquid wastes from reprocessing operations. *In: Proceedings of 5th International Fair and Technical Meetings of Nuclear Industries, 3–7 October 1978.* Basle, Nuclex, 1978.
11. *Handling and storage of high-level radioactive liquid wastes requiring cooling:* Vienna, IAEA, 1979 (Technical Report Series No. 191).
12. *Techniques for the solidification of high-level waste products.* Vienna, IAEA, 1978 (Technical Report Series No. 136).
13. *Characteristics of solidified high-level waste products.* Vienna, IAEA, 1979 (Technical Report Series No. 187).
14. Vitrification inches towards a solution. *Nuclear engineering international,* **25**: 13 (1980).
15. **Cohen, J.J. et al.** Lead encapsulation of nuclear waste: a risk assessment. *In: Transactions of the American Nuclear Society, Vol. 34.* La Grange Park, IL, American Nuclear Society, 1980.
16. **Ringwood, A.E.** *Safe disposal of high-level nuclear reactor wastes: a new strategy.* Canberra, Australian National University Press, 1978.

17. *Objectives, concepts and strategies for the management of radioactive waste arising from nuclear power programmes.* Paris, Nuclear Energy Agency of OECD, 1977.
18. **United Nations Scientific Committee on the Effects of Atomic Radiation.** *Sources and effects of ionizing radiation.* New York, United Nations, 1977.
19. *The effects on populations of exposure to low levels of ionizing radiation.* Washington, DC, US National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation, 1972.
20. **Cohen, J.J.** *Suggested nuclear waste management radiological performance objectives.* Livermore, CA, Lawrence Livermore Laboratory, University of California, 1979 (document UCRL-52626).
21. **International Commission on Radiological Protection.** *Problems involved in developing an index of harm.* Oxford, Pergamon Press, 1977 (ICRP Publication 27).
22. **International Commission on Radiological Protection.** Statement and recommendations of the 1980 Brighton meeting of the ICRP. *Annals of the ICRP,* **4**(3/4) (1980).
23. **Ahner, S. et al.** Engineered intermediate storage of solidified high-level wastes. A comparison of an air cooled and a water cooled concept. *In:* Simon, R. & Orlowski, S., ed. *Radioactive waste management and disposal.* New York, Harwood Academic Publishers, 1980.
24. *Underground disposal of radioactive wastes: basic guidance.* Vienna, IAEA, 1981 (Safety Series No. 54).
25. *Site selection factors for repositories of solid, high-level waste, and alpha-bearing wastes in geological formations.* Vienna, IAEA, 1977 (Technical Report Series No. 177).
26. **Orlowski, S.** The European Communities' research programme on the management and storage of radioactive waste: technical content, initial results, and future outlook. *In:* Simon, R. & Orlowski, S., ed. *Radioactive waste management and disposal.* New York, Harwood Academic Publishers, 1980.
27. **Nilsson, L.B. & Pappo, T.** Feasibility of safe terminal disposal of spent nuclear fuel. *International Atomic Energy Agency bulletin,* **22**(3/4): 63 (1980).
28. **Barbreau, A. et al.** Radionuclides migration in geological formations. *In:* Simon, R. & Orlowski, S., ed. *Radioactive waste management and disposal.* New York, Harwood Academic Publishers, 1980.
29. **Bradshaw, R.L. & McClain, W.C., ed.** *Project salt vault: a demonstration of the disposal of high-activity solidified wastes in underground salt mines.* Oak Ridge, TN, Oak Ridge National Laboratory, 1971 (document ORNL-4555).
30. *Final environmental impact statement, waste isolation pilot plant.* Washington, DC, US Department of Energy, 1980 (document DOE/EIS-0026).
31. *Proceedings of the 1980 National Waste Storage Program Information Meeting, Columbus, 9–11 December 1980.* Columbus, Office of Nuclear Waste Isolation, 1980 (document ONWI-212).

32. **Kuehn, K. & Verkerk, B.** Disposal in salt formations. *In:* Simon, R. & Orlowski, S., ed. *Radioactive waste management and disposal.* New York, Harwood Academic Publishers, 1980.
33. **Feates, F.S. et al.** Disposal of high-level radioactive waste into crystalline rocks. *In:* Simon, R. & Orlowski, S., ed. *Radioactive waste management and disposal.* New York, Harwood Academic Publishers, 1980.
34. **Baetsle, L.H. & Mittempergher, M.** Disposal in argillaceous formations. *In:* Simon, R. & Orlowski, S., ed. *Radioactive waste management and disposal.* New York, Harwood Academic Publishers, 1980.
35. **Beale, H. et al.** Conceptual design of repository facilities. *In:* Simon, R. & Orlowski, S., ed. *Radioactive waste management and disposal.* New York, Harwood Academic Publishers, 1980.
36. *Regulations for the safe transport of radioactive materials, revised edition.* Vienna, IAEA, 1973 (Safety Series No. 6).
37. **Anderson, D.R.** *Nuclear waste disposal in subseabed geologic formations: the seabed disposal program.* Albuquerque, NM, Sandia Laboratories, 1979 (document SAND 78-2211).
38. *The IAEA revised definition and recommendations of 1978 for the London Dumping Convention.* Vienna, IAEA, 1978 (document INFCIRC/205/Add.1/Rev.1).
39. *Proposed rule making on the storage and disposal of nuclear waste — statement of the position of the US Department of Energy.* Washington, DC, US Department of Energy, 1980 (document DOE/NE-0007).
40. *Evaluation of actinide partitioning and transmutation.* Vienna, IAEA, 1982 (Technical Report Series No. 214).
41. **Cohen, J.J. et al.** In-situ incorporation of nuclear waste in deep molten silicate rock. *Nuclear technology,* **13**: 76 (1972).
42. *Development of regulatory procedures for the disposal of solid radioactive waste in deep continental formations.* Vienna, IAEA, 1980 (Safety Series No. 51).
43. *Regulatory aspects of underground disposal of radioactive wastes.* Vienna, IAEA, 1980 (document IAEA-TECDOC-230).

Annex 1

GLOSSARY

A selection of terms and definitions from
Radioactive waste management glossary, Vienna, IAEA, 1982

acceptable limit Limit acceptable to the regulatory body.

actinide An element with an atomic number from 89 to 103, inclusive. All are radioactive.

annual dose limit Any of the annual *dose equivalent* limits for individual members of the public or workers recommended by the ICRP as part of its system of dose limitation in ICRP Publication 26.

barrier (natural or engineered) A feature which delays or prevents radionuclide migration from the waste and/or *repository* into its surroundings. An engineered barrier is a feature made by or altered by man; it may be part of the waste package and/or part of the repository. See *multibarrier*

becquerel (Bq) The SI unit of radioactivity, equivalent to 1 disintegration per second.

bedded salt A salt formation in which the salt is roughly horizontal, laterally extensive and relatively thin in the vertical direction (approx. 200 metres).

bioaccumulation The accumulation of a chemical element or compound by living organisms.

borosilicate glass 1. A supercooled liquid based on a random lattice of silica tetrahedra, modified with boron and other cations. 2. A glass composition used as an immobilization matrix for a radioactive waste.

calciner High-temperature process equipment used to convert waste solutions into a solid mixture of oxides (calcine).

can A sealed container for nuclear fuel or other material that provides protection from a chemically reactive environment and containment of radioactive materials produced during the irradition of the composite. It may also provide structural support. See *cladding*

canister A container (usually cylindrical) for solid radioactive waste. A canister affords physical containment; shielding is provided by a cask, but extra shielding may be required.

cladding (material) An external layer of material directly surrounding nuclear fuel or other material that provides protection from a chemically reactive environment and provides containment of radioactive materials produced during the irradiation of the composite. It may also provide structural support. See *can*

collective dose equivalent The collective *dose equivalent* to a population, expressed in units of man-sievert (man-Sv) . . . , that is, the sum of the products of the individual or *per caput* dose equivalents and the number of individuals in each exposed group in a population.

collective dose equivalent commitment (or collective effective dose equivalent commitment) The (effective) *dose equivalent commitment* multiplied by the number of individuals in the specified population. It is commonly expressed in units of man-sievert (man-Sv).

compartment Any part of the environment which may conveniently be considered as a single entity. (Used for environmental modelling.)

concept, waste management A basic idea from which a waste management practice may be developed. An example of a waste treatment concept is immobilization of liquid *high-level waste.*

conditioning of waste Those operations that transform waste into a form suitable for transport and/or storage and/or disposal. The operations may include converting the waste to another form, enclosing the waste in containers, and providing additional packaging.

confinement (or isolation) of waste The segregation of radionuclides from the human environment and the restriction of their release into that environment in unacceptable quantities or concentrations.

containment The retention of radioactive material in such a way that it is effectively prevented from becoming dispersed into the environment or only released at an acceptable rate.

contamination, radioactive A radioactive substance in a material or place where it is undesirable.

cost–benefit analysis A systematic examination of the positive effects (benefits) and negative effects (costs) of undertaking an action. For example, cost–benefit analysis may be used for optimization studies in radiation protection practice.

critical group For a given radiation exposure, the group of people whose exposure is considered acceptably homogeneous and typical of the persons receiving the highest dose.

deep-well injection The discharge of liquid wastes via deep wells into permeable but confined geological formations deep underground as a means of isolating the wastes from the human environment.

detriment The mathematical expectation of harm to a population incurred from a radiation exposure, taking into account not only the probabilities of each type of deleterious effect but the severity of the effect as well. Detriment, in general, also includes deleterious effects not associated with health, such as the need to restrict the use of some areas or products. If a linear dose–response relationship is assumed, the detriment associated with health may be directly related to the *collective dose equivalent commitment.*

dispersion The summed effect of those processes of transport, diffusion and mixing which tend to distribute materials from wastes or effluents through an increasing volume of water or air. The ultimate effect appears as a dilution of the materials.

disposal The *emplacement* of waste materials in a *repository,* or at a given location, without the intention of retrieval. Disposal also covers direct discharge of both gaseous and liquid effluents into the environment. See *storage*

dose A general term denoting the quantity of radiation or the radiation energy absorbed by a medium. Dose should be qualified as absorbed dose, *dose equivalent,* effective dose equivalent, effective *dose equivalent commitment,* committed dose, or collective dose. Dose alone may be used when it does not matter if reference is made to absorbed dose or dose equivalent.

dose commitment See *dose equivalent commitment*

dose equivalent The product of absorbed dose and quality factor and all other modifying factors necessary to obtain an evaluation of the effects of irradiation received by exposed persons, so that the different characteristics of the exposure are taken into account. The special name for the SI unit of dose equivalent is the *sievert* (Sv).

dose equivalent commitment (or effective dose equivalent commitment) For any specified decision, practice or operation, the infinite time integral of the *per caput* dose-equivalent rate for a specified population. The exposed population is not necessarily constant in numbers. It is commonly expressed in units of sieverts (Sv).

emplacement Placing the waste in its location for *storage* or *disposal.*

food-chain A figure of speech for the dependence for food of organisms upon others in a series, beginning with plants or scavenging organisms and ending with the largest carnivores. A web is a network or series of food-chains.

high-level waste 1. The highly radioactive liquid, containing mainly fission products, as well as some actinides, which is separated during chemical reprocessing of irradiated fuel (aqueous waste from the first solvent extraction cycle and those waste streams combined with it). 2. Spent reactor fuel, if it is declared a waste. 3. Any other waste with a radioactivity level comparable to 1 or 2. (Note that these definitions are not related to "high-level radioactive waste unsuitable for dumping in the ocean", as used in the London Dumping Convention.)

host rock (or host medium) A geological formation in which a *repository* is located.

immobilization of waste Conversion of a waste to a solid form that reduces the potential for migration or *dispersion* of radionuclides by natural processes during *storage,* transport and *disposal.*

ingest Take into the body by way of the digestive tract.

irradiated fuel Nuclear fuel that has been exposed to irradiation in a nuclear reactor. Irradiated fuel contains considerable amounts of radioactive fission products. Also called *spent fuel.*

isolation of waste See *confinement of waste*

justification, radiological The basis upon which a specified decision, practice or operation that is expected to result in human exposures to radiation is judged to have a positive net benefit.

model In applied mathematics, an analytical or mathematical representation or quantification of a real system and the ways that phenomena occur within that system. Individual or sub-system models can be combined to give system models.

multibarrier A system using two or more independent barriers to isolate the waste from the human environment. These can include the waste form, the container (*canister*), other engineered barriers and the emplacement medium and its environment. See *barrier*

optimization As used in radiation protection practice, the process of reducing the expected *detriment* deriving from radiation exposure of a population, through the use of protective measures, to as low as reasonably achievable, economic and social factors being taken into account.

overpack Secondary (or additional) external *containment* for packaged radioactive waste.

plasticity The property of a material, e.g. rock salt, that enables it to undergo permanent deformation without appreciable volume change or elastic rebound, and without rupture.

proliferation, nuclear A commonly used term for the acquisition of a nuclear weapons or nuclear-explosives capability by a nation or sub-national group.

repository An underground facility in which waste may be emplaced for *disposal.*

respository system A *repository* and all its supporting facilities.

risk A measure of the deleterious effects that may be expected as a result of a technology, traditionally quantified as the product of the probability and the consequence of the occurrence of an event or series of events.

salt dome A dome-like salt structure resulting from the upward movement of a salt mass, generally due to diapirism.

sievert (Sv) The SI unit of *dose equivalent.*

spent fuel Nuclear reactor fuel elements that have been irradiated in a reactor and have been utilized to an extent such that their further use is no longer efficient.

stochastic event A random event which can be predicted only by the probability of its occurrence.

storage The *emplacement* of waste in a facility with the intent that it will be retrieved at a later time.

transmutation Nuclear conversion transforming one element into another, naturally or artificially, (*a*) as a result of bombardment with ionizing radiation or nuclear particles or (*b*) by radioactive decay if the original element is radioactive.

transuranium nuclide A nuclide having an atomic number greater than that of uranium (i.e. greater than 92).

vitrification Any process of converting materials into a glass or glass-like form.

waste management All activities, administrative and operational, that are involved in the handling, treatment, conditioning, transportation, storage and disposal of waste.

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The safe disposal of high-level radioactive waste is a topic that has caused great concern to governments and the public alike. This book provides much needed information on this vital aspect of the nuclear power industry, and will be of particular interest in those countries that are now developing their nuclear technology and industry. It is especially important for policy-makers in the areas of health and the environment who need to keep themselves and the public well informed of the consequences of the development of nuclear power.

The technology required for the safe disposal of radioactive waste is considered to be already available. Although none of the options has yet been used or proven, conservative engineering practices and the use of multibarriers (combinations of man-made or natural barriers between the waste and the environment) may be expected to make up for the lack of knowledge and degree of uncertainty in predicting what may actually be required of a repository.

The options reviewed embody the principle that all radiation doses should be kept as low as can be reasonably achieved, economically and socially, both now and in the future. They should be selected on the basis of the effects of predicted doses of radiation on individuals and populations, and the probability of such doses occurring. It is recommended that the development of such standards of acceptability should be given priority by national and international authorities.