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Available Options for Waste Disposal [and Discussion]

F. Girardi and S. H. U. Bowie

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Available options for waste disposal

By F. Girardi

Commission of European Communities, Joint Research Centre,
Ispra Establishment, 21020 *Ispra* (*Varese*), *Italy*

Disposal of vitrified high-activity waste in properly selected deep geological formations is the option that absorbs most of present R&D and appears as an acceptable solution from a technical point of view. As regards safety, disposal projects under development appear to satisfy present radiological protection criteria, even if much uncertainty exists in both models and input data.

Other disposal concepts are, however, also being studied, with more limited effort. Their quantification in terms of costs and benefits is therefore rather uncertain at present. Among them the following are treated briefly: disposal in deep oceanic sediments, actinide separation and recycling, and extraterrestrial disposal. Taking into account the cost and development time required to bring these options to industrial operation, they should not be considered as alternatives to present projects of waste disposal, but rather as scientific research that may lead to industrial realization in a more mature nuclear age, in which the balance of costs, risks and benefits will be different.

Long-term storage of either spent fuel or vitrified waste, although not an alternative strategy of disposal, is an option that has considerable effects on waste management and the fuel cycle in general.

The three scenarios (disposal of vitrified waste in geological formations, extended storage, advanced disposal options) complement each other very well and none of them should be pursued at the sacrifice of the others.

1. INTRODUCTION

Nuclear waste is an inevitable consequence of nuclear energy, and R&D to set up safe and acceptable means for its disposal has been a constantly increasing fraction of nuclear energy research.

Disposal into a properly selected continental geological formation can be considered at present as the disposal means that could be technically implemented in a relatively short timescale. It is conceivable that a decision of such importance cannot be reached without showing that the solution proposed is the best of all possible solutions, enlarging perhaps somewhat the 'ALARA' concept, which imposes that all radiological practices should be optimized to deliver a radiation dose to man 'as low as reasonably achievable', economic and social factors being taken into account.

The R&D conducted so far, both on the various technological processes needed to implement geological disposal and also on alternative options, is probably sufficient to convince the decision-maker that the solution proposed is the best available, and to reach a decision on its implementation. However, this does not mean that the search for alternative options should be discontinued: the technological progress continuously changes the image of the 'optimum' solution, and practices now considered expensive or risky may, in a few years, become more common operations. Nuclear energy itself may change considerably, with new reactor types being commercialized as a result of technological progress and under the pressure of increased energy needs.

In this paper the present state of research on geological disposal of radioactive waste is reviewed briefly. A few alternative options, which have received special attention in the recent past or are under study at present, will also be reviewed and discussed briefly.

2. Disposal in continental geological formations

Waste disposal in continental geological formations is based on the principle that in the exposed Earth's crust it is possible to identify geological formations that by their intrinsic properties and the favourable geological context can isolate the waste disposed of into them for the time necessary for their decay to safe radioactivity levels (hundreds of thousands of years).

(*a*) *Rock types and site selection*

Several rock types have such suitable characteristics. In particular, crystalline rocks, clay and salt formations have been studied more extensively because they possess, in principle, intrinsic properties that make them particularly attractive for waste isolation.

(i) *Crystalline rocks* such as granite can be found in large homogeneous bodies, which are geologically stable and unattractive for exploitation of natural resources. Water migration through them occurs through minute fractures and fissures, frequently filled with alteration minerals with high retention properties for radionuclides. For deep waste repositories the path lengths to reach groundwater may be several kilometres.

(ii) *Clay formations* have a very low permeability, and water migration through them occurs very slowly; clays are excellent ion exchangers, and radionuclide migration will occur substantially more slowly than water. The plasticity of clays prevents the establishment of important fracture systems that could curtail geological isolation.

(iii) *Salt formations* are massive formations with high plasticity and minimum water content. Salt convergence around mined boreholes and galleries will reconstitute the original tightness in a few months' time. Salt has a particularly good heat conductivity.

Favourable rock properties must be coupled with a favourable geological context, which guarantees the maintenance of these properties over the time scale required for radionuclides to decay. A survey conducted by the Commission of European Communities with support of National Geological Institutes has shown that all European countries do possess several sites and regions with favourable geological contexts (CEC 1980).

(*b*) *Engineering feasibility and repository design*

Mining technology in salt and granite is now developed enough to allow detailed designs of conceptual repositories with minimal uncertainties.

Mining techniques in plastic clays for waste disposal have been extensively experimented upon by CEN/SCK Mol (Bonne 1985). A concrete-lined shaft with a diameter of 2.65 m has been sunk for 227 m in the Boom clay formation at Mol by a special technique of freeze–drilling. A horizontal gallery 34 m long has also been excavated by the same technique. A detailed examination of the rock properties at depth has successively shown that the rock stiffness is sufficiently high to allow the use of more conventional tunnelling machines, with substantial savings of perforation costs, and an additional experimental gallery has been constructed by such means.

The impact of the repository construction and operation on the properties of the formation itself has been the subject of very extensive research, particularly concerning thermal effects produced by the disposal of heat-producing waste (CEC 1982). As previously mentioned, salt formations can dissipate waste heat without local problems of thermal stresses, although there is a fear that unduly large heat loads might accelerate uplift of salt domes. In clay formations a large temperature increase might cause irreversible changes in the clay structure, which may diminish plasticity and impermeability of clay. Such changes are likely to remain confined to the immediate surroundings of the waste containers. In crystalline rock the fracture pattern can be disturbed by an excessively high temperature increase, with a consequent increase in rock permeability. It is, however, difficult to impose a general temperature threshold; the problem should be analysed on a system-specific base.

(*c*) *Safety of disposal*

The safety of waste disposal in continental geological formations has been subjected to intense research and debate in the last few years, particularly concerning the long-term safety aspects. The length of time for which safety must be guaranteed raises a number of issues that have never been considered for classical industrial safety, although they are not unique to nuclear energy. Indeed, the disposal of many types of industrial toxic wastes should be subjected to similar research and debate.

Although the literature on generic safety analysis of waste disposal is relatively abundant, there are few studies that are site-specific. The importance of this requirement, site specificity, should be stressed. The number of parameters required for a comprehensive safety analysis is so great that generic studies have inevitably only an orientative value. A review of current studies on safety analysis is outside the scope of this paper, and treatment of this point will be limited to show how these studies try to demonstrate compliance with the basic radiological protection criteria.

(i) *Crystalline rocks* have been subject of intensive research by the Swedish KBS group and by the Canadian AECL. The Swedish study (KBS 1983) is essentially deterministic: a reference failure scenario is assumed to occur (water percolation through the bedrock, considered as a porous-equivalent medium) and the pathway of waste radionuclides is calculated. Pessimistic assumptions are taken whenever there is uncertainty in input data. Several other scenarios are also considered for consequence analysis, without attempting to quantify their probability of occurrence. Extreme events are considered qualitatively, but not analysed in detail, owing to their negligible impact on safety.

Figure 1 shows the consequence of the various scenarios in terms of doses to nearby residents compared with radiological standards and natural conditions in Sweden. For the reference scenario such doses would be delivered at times exceeding 10^5 years after repository closure.

A similar approach is also being used by the Swiss Agency NAGRA in a conceptual study of waste disposal in Switzerland.

The Canadian approach (Wuschke 1984) is probabilistic: the failure scenarios are similar, but input data are subjected to a critical evaluation that results in a probability distribution function for each uncertain parameter. Random sampling of the parameters by a Monte Carlo code (SYVAC) allows results to be obtained in terms of 'risk', a practice that seems more in line with the most recent trends in radiological protection criteria.

(ii) *Clay formations*. Safety assessment has been carried out largely by the Joint Research Centre (JRC) of the CEC in cooperation with the Belgian CEN/SCK Mol. A first screening

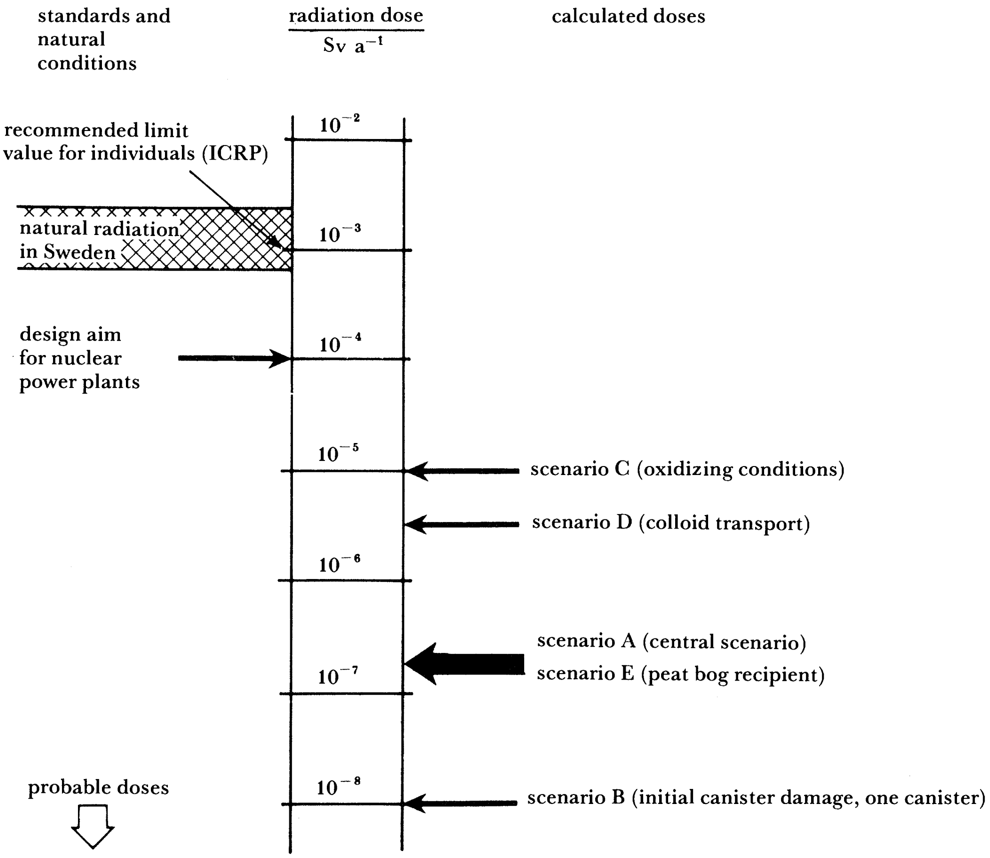

FIGURE 1. Waste disposal in granite formation: calculated doses to nearby residents for different scenarios (from KBS 1983).

of possible failure scenarios has been done by fault-tree analysis (D'Alessandro & Bonne 1981), which has also given a first indication of probabilities of the most relevant scenarios (faulting and glaciation). These phenomena have been analysed successively in more detail. Consequence analysis has been carried out by a probabilistic method similar to that employed by AECL. The combination of failure scenario probability and consequence analysis allows the calculation of probabilistic risks linked to the various scenarios (Bertozzi *et al.* 1984). The risk of health effects to most exposed individuals were estimated to be the order of 10^{-9} and 10^{-6} per year for the faulting and glaciation scenarios, respectively.

(iii) *Salt formations* are being studied in the Federal Republic of Germany, the Netherlands and Denmark. The German study PSE (Project Sicherheit Entsorgung) constitutes the most abundant source of information related to safety of waste disposal in a specific salt dome near Gorleben (PSE 1985). The approach developed is the classical worst-case analysis. The geology at the site is critically evaluated, concluding that the most critical scenario is the input of water through anhydrite layers in the initial post-closure period, when the porosity of backfilled boreholes and galleries is still high. The water coming into contact with waste would then be gradually 'squeezed' out of the salt dome by salt convergence. Pathways to man would then be via radionuclide transport through aquifers and biosphere.

The results obtained indicate individual doses to most exposed individuals of approximately 0.1 m Sv a^{-1} after 10000 years, with ^{237}Np and ^{99}Tc as major contributors. The bulk of the dose would be delivered by intermediate α-contaminated waste, and not high-level waste (HLW). This is due to the particular configuration of the repository, which would prevent input of water to the HLW waste zone.

A comprehensive study of 'Performance Analysis of Geological Isolation Systems' (PAGIS) in the European Community (EC) is being conducted by the CEC with participation of concerned laboratories in the EC and the JRC (Cadelli *et al.* 1984). In this study, reference sites in granite, clay, salt and seabed sediments have been selected and their characteristics defined; a few variants take account of the differences in the characteristics of the various potential sites in the European Community. Repository designs appropriate to each formation have been chosen and waste data reflect the processes developed by the nuclear energy industry in the EC. Possible release scenarios for each site have been selected and classified in three categories, which will be treated in different ways:

Normal evolution scenarios reflect the geological trends that have been identified at the sites, and for which an analysis including probabilistic treatment of data uncertainty will be carried out.

Altered evolution scenarios are those in which the normal evolution of the repository is altered by external events, largely of a probabilistic nature, that modify the conditions of the normal evolution. A risk concept is adopted for these scenarios, reflecting the probability of occurrence of scenarios, in addition to uncertainties in model data. This does not necessarily imply that scenario probabilities will be quantified in all cases: a conservative approach of considering the triggering event as certain may be adopted when the uncertainty of the probability data is large enough to make the data themselves meaningless.

Disruptive scenarios include those that may potentially cause a direct release to the biosphere, and are analysed only in terms of probability of occurrence.

The PAGIS exercise is planned in three phases, of which phase 1 (data collection) has been completed (Cadelli *et al.* 1984) and phase 2 (analysis) is under way. A third phase (data evaluation and recommendations) will complete the exercise, which is expected to end in 1987.

(*d*) *Disposal costs*

A study on waste disposal costs in salt clay and granite has recently been completed by the CEC (Venet *et al.* 1985). An overall cost of about 2×10^9 ECU (£1200 M) was calculated for repositories designed to store intermediate and high-level waste produced by a nuclear park of 25 $\mathrm{GW_e}$ operated for 30 years, assuming that disposal occurs 30 years after fuel discharge from the reactor and including costs of site validation, transport and interim storage. Figure 2 shows the scale effect for the different types of formations. The cost is similar for the reference scenario of 25 $\mathrm{GW_e}$, but the various formations show important differences for different repository size. If costs are discounted at a 3% yearly rate, the fee on the energy produced would be approximately 0.33×10^{-3} ECU/(kW h) (0.02 p/(kW h)) for the reference 25 $\mathrm{GW_e}$ case, or approximately 1% of the cost of the energy produced. As a comparison, the fee imposed on nuclear energy production by the U.S.A. Nuclear Waste Management Policy Act of 1982 for the disposal of spent fuel is 10^{-3} \$/(kW h) (or 1.4×10^{-3} ECU/(kW h), or 0.8 p/(kW h)).

Comparison of these figures shows that disposal of spent fuel would be considerably more expensive than disposal of vitrified waste, for the same energy produced. A recent NEA study on economics of the nuclear fuel cycle gave similar figures for the transport–interim-storage–disposal sequence (Crijns 1985). The cost of the overall fuel cycle, however, is substantially

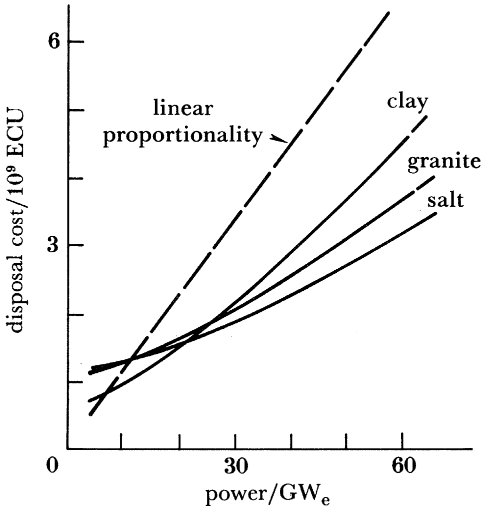

FIGURE 2. Scale effect of nuclear capacity on the total costs of disposal (ECU 1984) for different geological formations (from Venet *et al.* 1985).

the same for the two options because the additional cost of reprocessing–vitrification is compensated for by the uranium and plutonium credits and by the diminution of the disposal costs.

3. DISPOSAL INTO THE SEABED

Disposal into deep ocean sediments of selected ocean zones with high tectonic stability and limited water movements (midplate–midgyre regions) is being studied by several countries as a possible alternative to geological disposal in continental formations. The exchange of information and cooperation between different countries in the frame of an NEA-coordinated research programme is particularly active, so that the option is developed in a truly international environment (NEA 1984). Unfortunately this option suffers from severe non-scientific issues, which are not easily solved, as experience on sea-dumping operations has proved in recent years.

(a) *Sediment types and site selection*

The principles on which the option is based can be summarized as follows:

- some of the most stable geological formations on Earth are found underlying the deep oceans;
- sediment types under consideration are vast and far from human habitation;
- marine sedimentary formations are plastic, with a tendency to self-heal;
- the sediments are in general highly nuclide-absorbing and resistant to water movement;
- ice ages and other large climatic changes have little effect on the stability and uniformity of the deep ocean environments;
- the zones under consideration are well away from major continental fisheries and breeding areas, as well as communication routes, and sediments are devoid of useful resources.

Such zones can be found in both the Pacific and the Atlantic oceans, but two sites in the Atlantic Ocean have been selected for joint multinational experiments: Great Meteor East in the Madeira Abyssal Plan (400 miles west of the Madeira Islands) and the Nares Abyssal Plain (300 miles north of Puerto Rico). Several national and multinational research cruises have been carried out for both site characterization and emplacement experiments with instrumented penetrators.

(*b*) *Emplacement techniques*

Two basic techniques are currently under consideration:

(i) *Use of free-fall or boosted penetrators*. Several possible alternatives are shown in figure 3. Only free-fall penetrators have been used in *in situ* emplacement experiments at the chosen sites, although it is envisaged that for final implementation of the option one of the more sophisticated techniques shown in figure 3 may finally be preferable, because they allow high precision in positioning the penetrators and a closer network.

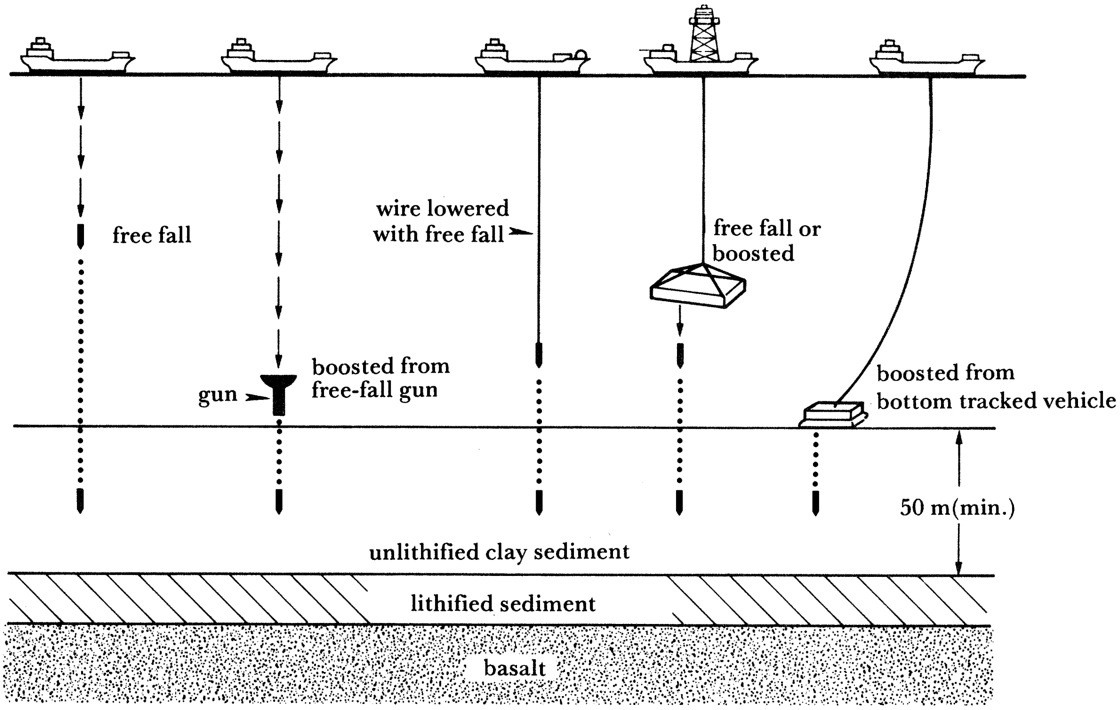

FIGURE 3. Different options for penetrator emplacement in deep ocean sediments.

In the experimental tests done, penetration depths exceeding 30 m have been reached with 1800 kg scaled penetrators. Several techniques for measuring penetration depths have been developed and the results appear generally in line with theoretical model calculations. The penetration depth obtainable for full-scale penetrators could be of the order of 50 m.

(ii) *Drilled emplacement*. Only theoretical feasibility studies have been made on this option. In a study conducted by Taylor Woodrow Construction Ltd for the CEC (Taylor Woodrow Construction Ltd 1985), the preferred solution was for a concrete semi-submersible platform to be maintained in position by a dynamic-positioning station-keeping system. The radioactive waste containers would be carried out to the platform and the waste canisters lifted out and formed into strings that would be lowered to the seabed by using a drillpipe and guided into the previously drilled hole.

Most of the operations for emplacing the waste are within the bounds of existing technology although there remain many uncertainties, particularly on how to recover from various malfunctions such as a dropped string of canisters.

(c) *Safety of the option*

The safety of the option is evaluated by methods derived from the studies of the continental disposal options. Preliminary evaluations of the long-term safety have been made for the penetrator option by both deterministic and probabilistic methods, for a base case of disposal of waste corresponding to 1000 GW_e a. The pathway to man considers corrosion of container – leaching of waste – diffusion of radionuclide through sediments – dispersion in the ocean – distribution through food chains to man. Exposure to man does not occur before 10^4 years at least, and peak annual individual doses do not exceed 6×10^{-8} Sv a^{-1}.

Several accidental scenarios considered do not seem to increase substantially the risk of public exposure. The critical process in the entire pathway seems to be radionuclide transport through sediment, which is assumed to occur by diffusion. Upward advection of pore waters exceeding 1 mm a^{-1} would alter the results significantly. Current research *in situ* should soon clarify this point.

The need of avoiding upward water movements brings in the requirement of avoiding large temperature increases in the sediment. For this reason extended interim storage (50 years) is assumed for waste to be disposed of. Ocean dispersion of radionuclides overcoming the sediment barrier has been calculated by a simple 6-box model of the ocean, which may underestimate critical paths. A more realistic and site-descriptive 18-box model is under development for sub-seabed assessment, based upon a hierarchy of more complex dynamical models.

(d) *Disposal costs*

In the study indicated above for the drilled option a cost of 0.0055 p/(kW h) (or 0.1×10^{-3} ECU/(kW h)) was calculated for emplacing vitrified waste obtained by a nuclear park of 200 GW_e operated for 25 years, assuming a 50 year interim storage before emplacement. In an engineering study of the penetrator option conducted by Ove Arup & Partners Engineering (Ove Arup & Partners 1985), a cost of 0.007 p/(kW h) (or 0.12×10^{-3} ECU/(kW h)) has been found for a reference scenario of disposal of 85 m^3 vitrified HLW annually (corresponding to 44 GW_e). This option is less sensitive to scale effects than the drilled emplacement option. When compared with the costs of continental geological disposal, and when account is taken of the many uncertainties inherent in the evaluation, it appears that the cost of ocean disposal should not be higher than that of continental options, and it might be substantially lower.

4. DISPOSAL IN SPACE

Conceptual studies for the disposal of nuclear waste in space have been made by, among others, U.S.A.–NASA and U.S.A.–DOE for several years, for the disposal of both military and commercial waste (NASA 1980). In its reference concept, disposal is based on a rather complex sequence of operations:

(i) conditioning of waste after 10 year decay into a cermet matrix, which is then fabricated into a 5000 kg spherical payload and loaded to a space shuttle vehicle;

(ii) transfer of the waste to a low Earth orbit;

(iii) transfer to a solar orbit by means of a transfer vehicle, which provides escape from Earth orbit, and by a solar orbit insertion stage, which circularizes the waste payload into the solar orbit disposal destination;

(iv) recovery of transfer vehicles and shielding for use in subsequent missions.

Safety problems in routine and accidental conditions seemed manageable, although the feasibility of deep ocean recovery of waste after a launching accident should be studied in more detail. A nuclear park of 200 GW_e, as forecast for the year 2000 in the U.S.A., would require 62 such missions per year. The cost of such a disposal option has not been calculated.

The study was terminated in 1980 with the proposition by NASA of a small experimental programme, which was not accepted. Unfortunately the study did not include disposal of selected waste fractions such as actinides and technetium, which would have made the cost–benefit picture of this option very different.

5. ACTINIDE SEPARATION

Although theoretical studies on the feasibility of burning actinides in nuclear reactors had been done before, the concept of actinide separation and nuclear transmutation of actinides was essentially studied in the decade 1973–82.

The Joint Research Centre of CEC at Ispra carried out in the period 1973–79 a programme on this option, including both experimental activities and theoretical evaluations (Mannone & Dworschak 1984; Schmidt *et al.* 1983). Experimental studies dealt particularly with actinide separation from high level waste. Three chemical flow-sheets were developed and verified at fairly large fully active scale (several kilograms of spent fuel), one at JRC (oxalate precipitation) and two at CEA–Fontenay-aux-Roses under a cooperative agreement with JRC. Activities on chemical separations also included an engineering assessment of the partitioning plant. Nuclear transmutation in several types of reactor was studied theoretically, and for one of them (homogeneous recycling in fast breeders) a conceptual design of the fuel element was also made. Several European laboratories were cooperating with JRC in this study. Two international technical meetings on this option were also organized by JRC under CEC–NEA sponsorship (CEC 1977, 1980).

In the U.S.A. the Oak Ridge National Laboratory (ORNL) coordinated a study, with the participation of several national laboratories and private enterprises, in the period 1977–80 (Croff *et al.* 1980). Chemical separation studies dealt with all types of waste from the fuel cycle, but only experiments at tracer levels were done. Nuclear transmutation in light water reactors and liquid metal-cooled fast breeder reactors (LMFBRs) was studied theoretically. The study also included an attempt at evaluating the cost–benefit in monetary terms.

Finally, the IAEA organized a Coordinated Research Programme on this option with contribution of several participating institutions, including the JRC and ORNL (IAEA 1982). The results obtained in the different laboratories combine rather well into a joint assessment, even though the various institutions gave different emphases to specific points that were felt of special importance.

It is generally agreed that actinide separation from waste is feasible, although a large effort is required to implement it. The cost of reprocessing may perhaps double when including partitioning, although a detailed evaluation of capital investments needed and of operational costs has not been made.

The neutron physics of actinide transmutation is favourable, and homogeneous recycling in LMFBRs appears the most promising way. Actinide fuels can be designed to meet the operational requirements of LMFBRs, although much research would undoubtedly be required on fuel behaviour in the reactor. The most critical problems would perhaps be in fuel refabrication, where all processes should be carried out remotely, owing to the high neutron output of recycled actinide fuels. The increase in cost of the entire fuel cycle has been estimated to be of the order of 5%.

The reduction obtained in the long-term risks would be controlled largely by the extent of chemical partitioning: a recovery of 98–99% is considered to be the maximum obtainable, and the same degree of separation could probably also be reached for other critical nuclides such as ^{129}I and ^{99}Tc. The diminution of potential radiological exposures of 'actinide-free' disposed waste would therefore be to between one fiftieth and one hundredth; a similar diminution could probably be obtained more easily and cheaply by imposing more stringent requirements on conditioning and disposal.

An undoubted advantage, which can hardly be quantified, would be that were an event to occur that had been underestimated by risk analysis, the consequences in the case of the disposal of an actinide partitioned waste would always be one fiftieth to one hundredth that of with disposing of a waste containing a non-partitioned actinide inventory. A second advantage could be that actinide partitioning opens the way to management schemes other than actinide recycling, such as separate conditioning and then disposal in geological formations, in the sea-bed, or even, for actinides or ^{99}Tc, in space. Other advantages could be added that have different starting points, such as separation of the heat-emitting nuclides ^{90}Sr and ^{137}Cs, or recovery of strategic noble metals. Although the cost of any of these schemes appears at present to outweigh the benefits, the cost–benefit ratio will not necessarily be the same in the next decades.

Actinide separation therefore seems to cope particularly well with a rather mature nuclear industry, as will be necessary if the energy demand of the next century should require a use of nuclear energy greater than that which may be forecast by present trends.

Recently (CEA 1984) the French working group on R&D on waste management chaired by Professor R. Castaing has recommended to the 'Conseil Supérieur' de la Sûreté Nucléaire, that R&D on actinide separation should be continued at a sufficiently high level to implement the process industrially by the end of the century.

6. Extended storage of spent fuel or vitrified waste

The storage of spent fuel or conditioned waste in engineered structures for several decades or even centuries is an operation that does not present, from a purely technical viewpoint, any special problems.

Whereas relatively expensive water cooling is needed for fresh spent fuel, cheaper dry-storage installations cooled by natural convection can be used for cooling times of several decades, preferably in centralized storage facilities. In the CEC study on costs of waste management previously mentioned, a cost of 250×10^6 ECU (£145M) was calculated for 30 years' storage of the waste produced by the reference nuclear park (25 $\mathrm{GW_e} \times 30$ years) in engineered structures, compared with 1250×10^6 ECU for the successive geological disposal operations. In the decay period between ten and several hundreds of years, the waste heat (be it spent fuel or vitrified waste) decreases with an approximate half-life of 30 years. Since repository dimensions are largely dependent on heat dissipation requirements, the cost of each 30 years of interim storage could probably be more than compensated for by the decrease of cost of disposal, also taking into account money discounting of the disposal operation. It would therefore seem that there is a net economic advantage in delaying implementation of disposal for several decades.

It is my opinion that while it is socially acceptable to delay the implementation of disposal, it is unacceptable to limit R&D to the setting up of interim storage facilities, leaving the next generation to solve the final disposal problem. On the contrary, technical feasibility of disposal should be clearly demonstrated on the required scale, and the know-how for a disposal operation should be maintained by operating demonstration repositories during the whole period of interim storage. In the same period research on alternative solutions should be continued, to be able to demonstrate, when requested, that the final solution adopted is the optimum one. In other words it should be very clear that the decision of maintaining interim storage is based on considerations of cost-effectiveness, and not on negligence towards future generations.

A final question that could be posed is whether, from a waste management point of view, it should be spent fuel or vitrified waste that is maintained in extended storage. Technically and economically there is not much difference in setting up and operating interim storage facilities for spent fuel or vitrified waste, and also the fuel cycle costs for the two options are probably comparable. Maintaining the vitrified waste in storage implies a commitment to geological disposal, be it in a continental formation or the seabed. However, spent fuel storage could allow other options to be implemented, provided that the necessary R&D is carried out successfully. A further advantage would be the possibility of adapting the fuel cycle operations to the progress of the energy industry in general, not only to that of waste management, both from a technological and economic point of view.

7. Conclusions

From the above it can be concluded that disposal in geological formations seems an adequate and cost-effective solution for present waste problems and, for the time being, appears to be the 'best' solution. Continental geological formations of various kinds are suitable candidates, and deep ocean sediments may turn out equally good if research on this option continues and the political issues are solved.

In a rapidly changing technological world, as in the present, it is hard to say whether geological disposal will remain the best solution indefinitely: there are alternative approaches such as separation of actinides and long-lived radionuclides followed by their transmutation, which appear within reach for a mature nuclear industry, as may be required for coping with future energy needs. Furthermore the disposal in space of a selected waste fraction may become a reasonable solution of the very long-term safety issues, given the progress in the space industry.

The various solutions mentioned above are not mutually exclusive, but might instead 'follow' each other, in an order depending on the type of technological progress during the next century.

The principle of the polluter as payer has become a general one, and radioactive waste management should be no exception. It is my personal opinion that the revenue collected for waste management through nuclear energy taxation should be used not only to set up a satisfactory solution to the waste problem for the time being, but also for continuing research to find the optimum solution.

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References

Bertozzi, G., D'Alessandro, M. & Saltelli, A. 1984 Waste disposal in a plastic clay formation, radioactive analysis for probabilistic scenarios. *CEC tech. Rep.* no. EUR 9641 EN.

Bonne, A. 1985 Characterization and behaviour of argillaceous rocks. Paper VI-5, presented at 2nd European Community Conference on Radioactive Waste Management and Disposal, Luxembourg.

Cadelli, N., Girardi, F. & Myttenaere, C. 1984*a* PAGIS, a European performance assessment of geological isolation systems. In *Radioactive waste management*, vol. 4, p. 219. Vienna: IAEA.
Cadelli, N. *et al.* 1984*b* PAGIS, summary report of phase 1. *CEC tech. Rep.* no. EUR 9220 EN.
CEA 1984 *Notes d'information CEA* no. 12, p. 3.
CEC 1980 Geological confinement of radioactive wastes within the European Community. *CEC tech. Rep.* no. EUR 6891 E.
CEC 1982 La charge thermique admissible en formations géologiques – conséquences sur les méthodes d'évacuation des déchets radioactifs. *CEC tech. Rep.* no. EUR 8179.
CEC 1977 Proc. 1st Tech. Meeting on Nuclear Transmutation of Actinides. *CEC tech. Rep.* no. EUR 5897 e,f.
CEC 1980 Proc. 2nd Tech. Meeting on Nuclear Transmutation of Actinides. *CEC tech. Rep.* no. EUR 6929 EN/FR.
Crijns, M. J. 1985 The economics of the nuclear fuel cycle. *NEA Newsle.* no. 4, pp. 4–9.
Croff, A. G., Blomeke, J. O. & Finney, B. C. 1980 Actinide partitioning program final report. I. Overall assessment. *ORNL tech. Rep.* no. ORNL-5566.
D'Alessandro, M. & Bonne, A. 1984 *Radioactive waste disposal into a plastic clay formation* (*Radioactive Waste Management Monographs*, vol. 2). London: Harwood Academic Publishers.
IAEA 1982 Evaluation of actinide partitioning and transmutation. *IAEA techn. Rep. Ser.*, no. 214. Vienna: IAEA.
KBS 1983 Final storage of spent nuclear fuel. *Tech. Rep.* no. KBS-3.
Mannone, F. & Dworschak, H. 1984 Chemical separation of actinides from high activity liquid wastes. *CEC–JRC Rep.* no. S.A./1.07.03.84.02.
NASA 1980 Analysis of nuclear waste disposal in space. *NASA Tech. Rep.* no. NASA-CR-161418.
NEA 1984 Seabed disposal of radioactive waste. Status report of the NEA Coord. Res. Programme.
Ove Arup & Partners 1985 Ocean disposal of radioactive waste: penetrator engineering study. *CEC Res. Contr.* no. 394-83-7-WAS-UK, final report.
PSE 1985 Projekt Sicherheitsstudien Entsorgung: Zusammenfassen der Abschluss bericht, Herausgegeben von der Ergebnisübersicht, Berlin.
Schmidt, E. *et al.* 1983 Assessment studies on nuclear transmutation of by-product actinides. *CEC–JRC Rep.* no. S.A./1.05.03.83.13.
Taylor Woodrow Construction Ltd 1985 A feasibility study of the off-shore disposal of radioactive waste by drilled emplacement. *CEC Res. Contr.* no. 256-81-7-WAS-UK; final report.
Venet, P. *et al.* 1985 Cost and financing of radioactive waste disposal. Paper VII-5, presented at 2nd European Community Conference on Radioactive Waste Management and Disposal, Luxembourg.
Wuschke, D. M. 1984 Environmental and safety studies for nuclear fuel waste management: preliminary results of 2nd post-closure assessment. In *Proc. 16th Information Meeting of the Nuclear Waste Management Programme* (AECL-TR-218), p. 187.

Discussion

S. H. U. Bowie, F.R.S. (*Tanyard Farm, Clapton, Crewkerne, Somerset, U.K.*). (1) Clay minerals are normally good ion exchangers, but saturation levels with a particular radionuclide can be reached quickly and desorption follows. This requires careful investigation before being employed in any barrier technology.

(2) The possible disposal of high-level waste by free-fall penetrators seems fraught with difficulties and I wonder, in particular, if there is any evidence that satisfactory sealing of the sediments along the path of the penetrator will be possible.

F. Girardi. (1) Backfilling materials have several functions, such as preventing the inflow of water and retarding the outflow of radionuclides. For this last function ion exchange is a useful property, but providing the proper chemical environment for minimizing radionuclide mobility is perhaps more important. The final composition of an optimized backfill material has still largely to be developed.

(2) According to model calculations the elastic properties of deep sediments should be such as to close the hole behind the penetrator. Experimental small-scale tests carried out with centrifuges on reconstituted sediment layers seem to confirm predictions. In-situ tests are currently being designed and organized, and an answer to this key question should be obtained in 2–3 years.