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NWMO BACKGROUND PAPERS
6. TECHNICAL METHODS

6-5 RANGE OF POTENTIAL OPTIONS FOR THE LONG-TERM MANAGEMENT OF USED NUCLEAR FUEL

Phil Richardson & Marion Hill
Enviros Consulting

NWMO Background Papers

NWMO has commissioned a series of background papers which present concepts and contextual information about the state of our knowledge on important topics related to the management of radioactive waste. The intent of these background papers is to provide input to defining possible approaches for the long-term management of used nuclear fuel and to contribute to an informed dialogue with the public and other stakeholders. The papers currently available are posted on NWMO's web site. Additional papers may be commissioned.

The topics of the background papers can be classified under the following broad headings:

1. **Guiding Concepts –** describe key concepts which can help guide an informed dialogue with the public and other stakeholders on the topic of radioactive waste management. They include perspectives on risk, security, the precautionary approach, adaptive management, traditional knowledge and sustainable development.
2. **Social and Ethical Dimensions** - provide perspectives on the social and ethical dimensions of radioactive waste management. They include background papers prepared for roundtable discussions.
3. **Health and Safety –** provide information on the status of relevant research, technologies, standards and procedures to reduce radiation and security risk associated with radioactive waste management.
4. **Science and Environment –** provide information on the current status of relevant research on ecosystem processes and environmental management issues. They include descriptions of the current efforts, as well as the status of research into our understanding of the biosphere and geosphere.
5. **Economic Factors** - provide insight into the economic factors and financial requirements for the long-term management of used nuclear fuel.
6. **Technical Methods** - provide general descriptions of the three methods for the long-term management of used nuclear fuel as defined in the NFWA, as well as other possible methods and related system requirements.
7. **Institutions and Governance** - outline the current relevant legal, administrative and institutional requirements that may be applicable to the long-term management of spent nuclear fuel in Canada, including legislation, regulations, guidelines, protocols, directives, policies and procedures of various jurisdictions.

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Acknowledgement:
The authors gratefully acknowledge the permission of United Kingdom Nirex Ltd to use the artist's impressions of the various concepts discussed herein.

EXECUTIVE SUMMARY

Methods for the long-term management of used nuclear fuel and other long-lived and highly active radioactive wastes have been under investigation in various countries for about the past forty years. A large number of methods have been suggested and there is sufficient information available to prioritize them for future work. This paper provides a summary of recent published assessments of management options for used fuel and, based on these assessments, suggests that they can be placed in three categories of differing levels of interest for further R&D.

Sixteen fuel management options are considered in the paper. These include underground disposal, storage above ground, storage underground, sub-seabed disposal, disposal in space, and partitioning and transmutation. For each option there is a brief description and a summary of published assessments. These summaries use environmental, technical, economic and social and ethical criteria taken from other reviews of options. The intention throughout is to give fair treatment to all the options and not to dismiss any of them out of hand.

It is suggested that there are only three long-term management options that are of '*considerable interest'* for future R&D. These are underground disposal in a deep repository, storage above ground and storage underground. These three options are being assessed in detail or implemented in many national programs worldwide.

Four options considered to be of '*some interest'* for future R&D are partitioning and transmutation, reprocessing, underground disposal in an international deep repository and storage in an international facility. The first two of these are not complete management options for used fuel because there would be residual wastes to store or dispose of, and neither could be implemented in the near future. International storage and international underground disposal are options that may become more practicable and desirable over the next few years than they seem now, at least for some countries.

Based on recent assessments, the other nine options are judged to be of '*very little interest'* now. They are still advocated by a few organizations and individuals but are not part of any national programs. Some are ruled out by international conventions.

1. INTRODUCTION

The purpose of this background paper is to provide a short factual overview of all potential management options for used nuclear fuel in Canada. It aims to assist in their prioritization for further work and thus aid selection of the option or options to be implemented. This will be done in a way that is commensurate with, for example, the Draft Regulatory Policy (P-290) issued in April 2003 by the Canadian Nuclear Safety Commission, intended to promote options that are '*consistent (with) national and international standards and practices for the management and control of radioactive waste'*.

1.1 Background to the Current Situation in Canada

The decision was made many years ago in Canada to store used fuel intact after its removal from commercial nuclear reactors and not to reprocess it so as to recover uranium and plutonium. This led to the development of a number of interim storage facilities. The used fuel is initially stored underwater in pools and after some years is transferred to concrete casks for dry storage. These facilities have been operating safely for over 25 years. Canada currently has one of the world's largest inventories of stored used fuel [Bunn et al 2001]. This is mainly because CANDU reactors burn natural uranium rather than enriched uranium, so they require a larger volume of fuel per unit of electricity produced than, for example, pressurized water reactors.

In 1978 the Nuclear Fuel Waste Management Program (NFWMP) was launched by the Federal government and the provincial government of Ontario, in order to assess disposal options for used nuclear fuel. The NFWMP focused on underground disposal of packaged fuel in a deep geological repository in the rocks of the Canadian Shield. Over the period 1979-1981 it was decided to engage in a three stage process, involving generic research and concept proving, to be followed by site selection and development.

The research phase of the NFWMP ran from 1981-92, after which Atomic Energy of Canada Ltd (AECL), who were managing the program, were instructed to prepare a 'conceptual environmental impact statement', which was submitted to the government authorities in 1994. A nine month public review period was followed by a twelve month, three stage, public hearing process, which began in March 1996 and was managed by the Canadian Environmental Assessment Agency. A specially appointed panel was responsible for the whole concept assessment process, which ended in March 1998. The panel found the concept to be technically safe but recommended that the next stage, site selection, should not proceed until a number of steps had been carried out by government. These steps included the achievement of a broader public consensus that underground disposal would be the best option.

In order to help achieve this, a new Waste Act was passed in 2002 that instructed the producers of the used nuclear fuel to establish the Nuclear Waste Management Organization (NWMO) as an independent body to manage the new process.

1.2 Types of Potential Options for Used Fuel

According to the 2002 Nuclear Fuel Waste Act, NWMO is mandated to conduct a study setting out its proposed approach for long-term management of used nuclear fuel, which must include examination of three main options:

- deep geological disposal in the Canadian shield, based on the concept described by AECL in its environmental impact statement
- storage at nuclear reactor sites
- centralized storage, either above or below ground.

There are other options, including those in which used fuel is treated in some way to reduce its toxicity or its volume, or both. An example is partitioning and transmutation, in which the most toxic constituents of the fuel are separated out and converted to less toxic forms. A further class of options is those in which disposal is not to an underground repository but by some other means, for example by emplacement under the bed of the deep ocean or by ejection into space. All these sorts of options have been studied in the past in various countries and in varying degrees of detail, and there is enough information available to prioritize them for further work.

1.3 Structure of this Background Paper

In Section 2 of this background paper the possible management options are identified. The aim in this section is to include all the options that have been suggested in the literature, regardless of whether they are technically available or economically or politically attractive. Section 3 summarizes the criteria that have been used to assess options in recent reviews in other countries. Sections 4-19 contain brief descriptions of each option and summaries of published assessments of them. The intention in these sections is to treat all the options in the same degree of detail, as far as possible, and not to dismiss any of them out of hand. The paper concludes with a suggested categorization of options as being of considerable, some or very little interest for future R&D, based on the published assessments.

2. IDENTIFICATION OF OPTIONS

As indicated above, it is essential for NWMO to consider three options: disposal underground in the Canadian Shield, storage at reactor sites and centralized storage above or below ground. A major difference between the three options is that disposal is, by definition, permanent, because there is no intention to retrieve the waste (even though it would be possible to do so). Storage can be viewed as temporary, because it is envisaged that after a long period it will be followed by some, as yet unspecified, form of treatment and disposal. It can also be viewed as permanent, because when storage begins it is envisaged that it will continue indefinitely. It could also be argued that another difference between the three options is that with storage no decision needs to be made as to whether the used fuel is waste or whether it is a resource, some of the constituents of which might be recovered for use in the future. It is implicit in the underground disposal option that the fuel is declared to be a waste for which no further use is foreseen.

Within the main storage and disposal options there are a number of variants to be considered. At-reactor storage, centralized surface storage and centralized underground storage would all involve monitoring of the waste and its surroundings, so that remedial action could be taken if any leaks occurred. How much monitoring would be done is a decision that needs to be taken. It may be best addressed by defining various storage options with different monitoring arrangements, for example from continuous remote or manned monitoring to inspection once a year. Similarly there are decisions to be made about how and what to monitor in a deep underground repository, both before and after it is closed, and these could also be addressed by defining various different repository designs.

In the case of underground disposal, another decision to be made is whether to aim to keep the repository open for some period of time, with the waste in a closely monitored and relatively easy to retrieve state, before finally backfilling and sealing the repository. The alternative is to carry out backfilling and sealing immediately or very soon after waste emplacement. If the repository is to be kept open it is necessary to have some idea of how long for in order to include appropriate design features.

A number of observers have pointed out that, in addition to choosing between long-term storage and disposal, it is also necessary to decide whether to treat the used fuel in some way so as to reduce its toxicity or volume or both. The wastes and other materials produced by the treatment processes would need to be placed in long-term storage or disposed of, unless they could be recycled or re-used in some way. Developing the new treatment process and building the new treatment facilities would take time. Meanwhile the used fuel would have to be stored at reactors or centrally. The principal treatment processes to consider are those that would separate out the most toxic constituents of the fuel.

Another class of long-term options is those that involve disposal by means other than emplacement in a deep underground repository in the Canadian Shield. Examples are disposal beneath the bed of the deep ocean, disposal in ice sheets and disposal by ejection into outer space. Each of these options could be preceded by treatment to reduce the toxicity or volume of the fuel, or only by storage while the equipment and facilities to implement the disposal option are developed.

It can be seen from the above that a large number of combinations of treatment, long-term storage and disposal options could be considered. So as to keep this paper short, the approach adopted here is not to look at all of these in the same detail but instead to examine a relatively small number of combinations that embody the main features of the alternatives. Table 1 shows these combinations. The table shows the fuel treatment method involved in each option, whether the option involves long-term storage or disposal, and the storage or disposal method. Interim storage is not shown in the table because it is common to all options (although the length of the storage period would vary from one option to another).

Table 1 Management Options Considered in this Paper

Name of Option	Treatment Process	Long-Term Storage Method	Disposal Method
Partition and Transmutation	partition, transmutation, solidification and packaging of residual wastes	centralized, above or below ground, for residual wastes	any shown below, for residual wastes
Reprocessing	fuel dissolution, separation of uranium and plutonium, solidification of wastes	centralized, above or below ground, for residual wastes	any shown below, for residual wastes
Above Ground Storage	packaging	a) at reactor b) centralized	none
Underground Storage	packaging	centralized	none
International Storage	packaging	centralized, below ground	none
Underground Disposal	packaging	none	deep repository
International Underground Disposal	packaging	none	deep repository
Emplacement in Deep Boreholes	packaging	none	deep boreholes
Direct Injection	dissolution	none	injection into deep rocks
Rock Melting	none or packaging in heat-resistant containers	none	emplacement in deep cavity or borehole
Disposal at Sea	packaging	none	emplacement on the bed of the deep ocean
Sub-Seabed Disposal	packaging	none	emplacement under the bed of the deep ocean
Disposal in Ice Sheets	packaging	none	emplacement in stable ice sheets
Disposal in Subduction Zones	packaging	none	emplacement in offshore trench at subduction zone
Disposal in Space	packaging	none	ejection into outer space
Dilute and Disperse	dissolution, dilution	none	discharge liquid to sea

3. OPTION ASSESSMENT CRITERIA

This section sets out the criteria that are used in Sections 4-19 to summarize previous assessments of options for the long-term management of used nuclear fuel. The criteria are based on those used in various studies of options for the management of long-lived and highly radioactive wastes (see, in particular, Hill and Gunton 2001). No attempt is made to employ all the criteria from published studies because this would make the discussion long and complex. Instead a few criteria are extracted so as to address the key features of the options in Table 1 and the differences between them. For ease of subsequent use the criteria are grouped under four headings: environmental, technical, economic, and social and ethical.

3.1 Environmental Criteria

Environmental criteria are those related to risks to human health and those related to direct impacts on the environment. Appropriate types of criteria are often derived by considering the factors that would usually be considered in an environmental impact assessment for a nuclear or other industrial facility [eg Hill and Gunton 2001].

The health risk criteria can be sub-divided in various ways. For example, it is possible to use criteria for:

- the public and workers
- individuals and populations
- routine operations and accidents (including natural disasters and human errors)
- short-term and long-term risks
- local, regional and global risks
- radiological and non-radiological risks.

The health risks to be considered are those associated with all the stages of an option, including the construction and operation of facilities, transport of used fuel and the very long-term (eg the period after sealing of an underground repository).

Criteria related to direct impacts on the environment include those for radiological and non-radiological risks to the health of flora and fauna, and those for contamination of soil, groundwater and surface water (fresh and marine) by radioactive and non-radioactive substances. There can also be criteria for environmental effects such as the visual impact of any new facilities, noise during operations and use of natural resources (land, rocks and minerals used in construction, water). Climate change effects of non-radioactive pollutants would also be included here (eg emissions from vehicles used to transport nuclear fuel and to transport construction materials for any new facilities that are needed for an option).

For the summaries of assessments in Sections 4-19 all these types of criteria are borne in mind. However, the summaries focus on the potential of an option to suffer accidents with high consequences for human health and that would cause widespread radiological contamination of the environment. This is because possible accidents are taken to be of high concern in many assessments [eg EKRA 2000].

3.2 Technical Criteria

Two types of technical criteria to consider are those related to technical feasibility and those related to technical evaluations of safety. All of the options identified in Section 2 are believed to be technically feasible in the sense that, given enough R&D, they could in due course be implemented. What distinguishes between the options is the amount of effort, time and funding it would take to develop them to the implementation stage. The appropriate criterion for the purpose of this paper is thus how much R&D would be required before the option could be used on the scale necessary to deal with all of Canada's used nuclear fuel (see also Hill and Gunton [2001]).

Similarly, it can be assumed that all the options identified in Section 2 could be designed to be safe in the sense that they would meet the appropriate Canadian regulatory requirements. The distinction between the options is in how much effort and money this would take, in other words how easy or difficult it would be to 'make the safety case' for the option. Subsidiary issues such as ensuring that the safety case is transparent [Wilkinson et al 2002] can be included in a criterion about the resources needed to make a credible safety case.

3.3 Economic Criteria

The obvious economic criteria are the capital and operating costs of an option. The latter include costs of maintenance and repair, costs of monitoring, and costs of decommissioning. A less obvious criterion is the cost of insuring against accidents [Wilkinson et al 2002; Hill and Gunton 2001]. All operating nuclear facilities have to have nuclear liability insurance and facilities for the long-term management of used nuclear fuel would be no exception. What is not clear at present is for how long the insurance would be required. For example, if a sealed underground repository is monitored for thousands of years would it be necessary to have insurance over all this time so that waste could be retrieved if something untoward is found? In the summaries of assessments in Sections 4-19 the possibility that long-term insurance would be needed is examined for each option and considered as a potential cost where relevant.

Different kinds of economic criteria are those related to the financial benefits that adopting an option could bring to an area or areas of Canada, or to the whole country [Wilkinson et al 2002; Hill and Gunton 2001]. Most fuel management options would involve creating jobs, for example in R&D, in transport and in the construction of new facilities. In many instances employment would be increased for decades, simply because it would take that long to deal with all the used fuel. It is important to consider such economic benefits in the final decision on the fuel management option to be implemented. However, these potential benefits are not considered to be a significant factor in the process of selecting options for further work and so are omitted from the assessment summaries in Sections 4-19.

3.4 Social and Ethical Criteria

The social and ethical criteria considered in the summaries in this paper are (see Hill and Gunton [2001]; Wilkinson et al [2002]):

- the extent of the responsibilities that an option places on society (eg to monitor and maintain a facility, to transfer knowledge to successive generations);
- the stability of an option to socio-political changes (national and international);
- the ability to exert direct control over the used fuel (especially to monitor it and, if necessary or desirable, retrieve it and place it elsewhere);
- the extent to which an option complies with international treaties and conventions.

The societal responsibilities criterion is intended to cover all the 'burdens' that an option could place on the next and successive generations. For example, options such as long-term storage entail monitoring, maintenance and repair of stores, and possibly their replacement at intervals. There could also be an obligation to maintain the capability to respond to radiological accidents. The stability to socio-political changes criterion is included because lack of stability is so often mentioned as a disadvantage of storage as compared to disposal.

The criterion for ability to exert direct control over the used fuel can be taken as covering a number of other attributes of options. These include reversibility (if something goes wrong or a better option is found) and the ability to monitor the performance of the option. Compliance with international treaties and conventions is included as a social and ethical criterion because failure to comply would, in most instances, primarily have social and political repercussions and would be regarded as ethically incorrect.

3.5 Criteria Not Used

The four criteria that are not used in the assessment summaries in this paper but that are included in some reviews of long-term radioactive waste management options are those dealing with sustainability, intergenerational equity, general ethical considerations and public acceptability. Sustainability is omitted because how sustainable an option is depends on a number of features that are addressed by other criteria. These features are mainly risks to human health and the environment, and financial costs, but could also be taken to include societal responsibilities (see Section 3.4). Using sustainability as a separate criterion could thus imply double counting. Similarly intergenerational equity can be considered to be addressed by other criteria. A further difficulty with sustainability and intergenerational equity as criteria is that they are defined in different ways by the advocates of the various options. In particular, both advocates of disposal and advocates of storage use sustainability and intergenerational equity arguments to make the case for their chosen option [House of Lords Select Committee, 1999].

General ethical considerations are not used as criteria in this paper because it is difficult to define them. Also, some aspects that might be included as general ethical considerations are addressed by the specific ethical and social criteria about responsibilities and the ability to exert control (see Section 3.4).

Any attempt to use 'public acceptability' as a criterion would imply that those who are carrying out the assessment of options can predict what the public will find acceptable. It could also be taken to imply that decisions will be taken without consulting the public. Both implications are undesirable. A better approach is to publish the assessment of options so that the public can judge for themselves and this is the approach used in most recent published reviews. This paper is to be published and NWMO is required by law to have a program for public consultation on its proposed approach (or approaches) to the management of used nuclear fuel.

4. PARTITIONING AND TRANSMUTATION

4.1 Description

Partitioning and transmutation (P&T) was first suggested in the late 1960s as a means of reducing the long-term toxicity of radioactive waste. The aim of P&T is to produce shorter-lived or stable nuclides and so reduce the need for management of radioactive wastes in the long-term.

Transmutation is the changing of one type of atom to another as a result of a nuclear reaction, most usually as a result of bombardment with neutrons. These can be produced either by a nuclear reactor or in a particle accelerator. The radionuclides in the waste that are chosen for transmutation have to be chemically separated from the other materials. This is known as partitioning. It is necessary to avoid unwanted reactions that would increase the time required to transmute the radionuclide of choice and lead to the formation of other long-lived radionuclides, which would make the process less efficient.

P&T has been demonstrated on a laboratory scale but much further work is required to allow the equipment to be scaled-up to commercial size. The option is currently being investigated in Japan, France, USA, Russia, the Republic of Korea, Spain and Germany. Several other countries such as India, China, Belgium, the Netherlands and Italy have government-sponsored P&T projects, or take part in European Commission projects [Nirex 2002b]. In some countries, most notably the US, P&T is primarily being considered as a means of dealing with unwanted nuclear weapons and surplus plutonium. Other countries (eg the UK) have decided not to undertake R&D on P&T but to maintain a watching brief on work elsewhere [Cummings et al, 1996a and 1996b].

4.2 Summary of Assessments

There is general agreement that partitioning and transmutation (P&T) is not a complete option for the management of used nuclear fuel because there would be residual wastes to deal with, either by long-term storage or by disposal (see, for example, Wilkinson et al [2002]). It is also agreed that several decades more R&D would be required before P&T could be applied on a large scale (see, for example, House of Lords Select Committee [1999]). Some studies conclude that P&T will never be worthwhile for used nuclear fuel from existing reactors but is best suited to be incorporated in completely new nuclear fuel cycles, especially those using pyrochemical reprocessing (see, for example, Nirex [2002a], Cummings et al [1996a]).

From published reviews it appears that P&T would be expensive to implement for Canadian used nuclear fuel because of the R&D required, the new facilities that would need to be built and the residual wastes that would need to be managed. It would be difficult to assess the health or environmental risks that P&T would give rise to, given the early state of development of the option, or to estimate how easy it would be to make the safety case for P&T processes. The option could meet most of the social and ethical criteria (see Section 3.4). One possibility is to view P&T not as an option that would be chosen for implementation now, but as an option that might be implemented after storage of the used fuel for a fairly lengthy period, when technology has advanced.

5. REPROCESSING

5.1 Description

Reprocessing is the chemical separation of uranium and plutonium from used nuclear fuel so that they can be used again. It was originally developed to obtain plutonium for nuclear weapons manufacture, but was then taken up on a commercial basis. Most of the uranium and plutonium produced by reprocessing are currently stored, awaiting decisions on their re-use or declaration as waste. It was intended that much of these would be used in fast breeder reactors but development of such reactors has been abandoned. Some uranium and plutonium is used to make 'mixed-oxide' fuel (MOX) that is burnt in pressurized water reactors in various European countries.

At the present time commercial reprocessing of used fuel takes place only at Sellafield in the UK (by BNFL) and at Cap la Hague in France (by COGEMA). Some other countries send their used fuel to one or both of these facilities for reprocessing, but many others have taken the decision not to reprocess. There was large scale reprocessing in the Soviet Union but now most fuel in eastern European countries is being stored. The US ceased reprocessing in the 1980s when it was decided not to generate any more separated plutonium for possible civil or defense use.

The main attraction of reprocessing as a means of managing used fuel is that it allows the uranium and plutonium to be recovered for re-use. The remaining high level liquid waste can be converted to a stable solid (eg by vitrification) and has a much smaller volume than the original fuel. For some fuel types (especially the uranium metal fuel used in UK Magnox reactors) reprocessing is desirable because the fuel is not in a sufficiently stable physico-chemical form to be placed in long-term storage or disposed of.

5.2 Summary of Assessments

Reprocessing is not considered in most reviews of management options for spent fuel because the countries in question have already taken the decision as to whether to reprocess or not, usually based on factors other than waste management. These factors are typically the economics of recycling plutonium and uranium, and non-proliferation considerations. This is the situation in Canada. It is much less costly to manufacture new fuel for CANDU reactors than to reprocess used fuel and recycle the uranium and plutonium. Also, Canada has elected not to be a nuclear weapons state and has wished to avoid separating out fissile materials that could be used in a weapons program in Canada or elsewhere.

The only countries that are developing reprocessing facilities for civil purposes are those that have an interest in advanced nuclear fuel cycles (eg Japan) [IAEA 1997]. For other countries it could be argued that it would only be worthwhile to reprocess used fuel if reprocessing produced waste that was much more suitable for long-term storage or disposal, and/or if the recovered uranium and plutonium could be re-used. Experimental work on the likely long-term behavior of used fuel and vitrified HLW suggests that neither has appreciable advantages over the other. Substantial R&D would be needed to find out whether it would be feasible and safe to re-use all the plutonium and uranium that would be generated by reprocessing in Canadian reactors. In addition, the short-term health and environmental risks of reprocessing would be high compared with keeping fuel intact, its costs would be high and it would be in direct contravention of the policy of Canada's nearest neighbor, the US.

6. ABOVE GROUND STORAGE

6.1 Description

Suggestions for long-term above-ground storage broadly fall into two categories:

i) conventional stores of the type currently used for interim storage, which would require regular replacement and repackaging of waste (perhaps every century or two);

ii) 'permanent' stores that would be expected to remain intact for very long periods (perhaps tens of thousands of years) [Nirex 2002b].

The former category of store is derived from the principle of '*guardianship*', where future generations continue to monitor and supervise the waste. If this type were adopted as a long-term waste management method for used nuclear fuel there would be a requirement for continued repair and maintenance to be guaranteed, to ensure the safety of people and the surrounding environment. Although ponds and pools are used for interim storage, a long-term above-ground store would probably be dry. It could consist of concrete casks (as currently used at Canadian reactors) or an air-cooled vault (such as that built at Fort St Vrain in the US).

The 'permanent' stores are often referred to as '*monolith*' stores or '*mausoleums*'. They would be sealed and would not need regular repair and maintenance but would be monitored. It would be possible to construct an above-ground store at each reactor site or to have one centralized facility, at a reactor site or elsewhere.

6.2 Summary of Assessments

As indicated in Section 6.1, there are two types of store to consider: 'conventional' (ie buildings of the sort used for interim storage and that would need to be replaced every century or so), and 'permanent' (ie sealed structures designed to last for thousands of years without maintenance). The technology for interim storage is well-developed but very little has been done on permanent stores.

There is agreement that conventional stores that are well designed, operated and maintained would pose low risks to the public. They would be more vulnerable to terrorist attacks and acts of war than sealed underground repositories but the probabilities of such events occurring are usually assumed to be low. If the stores became vulnerable to the effects of climate change (eg flooding as a result of sea level rise) the fuel could be moved to new stores at less vulnerable sites. There would be risks to workers during the maintenance of stores and particularly during their replacement and during any repackaging of the fuel [Hill and Gunton 2001; Nirex 2002a; Bunn et al 2001]. If civilization collapsed conventional stores would fall into disrepair, the fuel would become exposed to the weather, and radionuclide release to atmosphere, soil and groundwater would occur. Permanent stores would be expected to pose lower risks to the public, workers and the environment than conventional stores. Perhaps their greatest risks would be associated with human intrusion if inspection regimes and monitoring systems failed [Nirex 2002a].

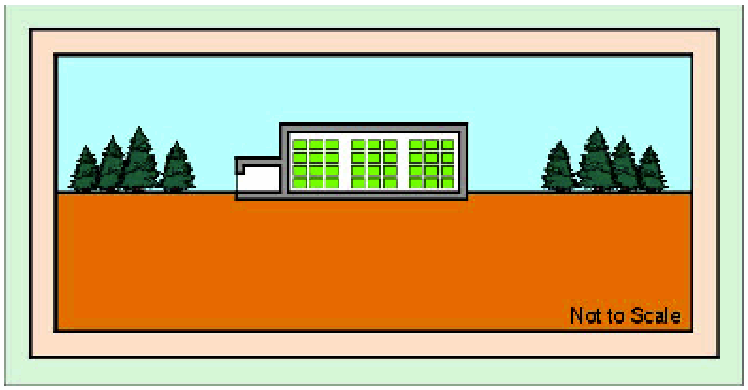

Figure 1 Artist's Impression of Above Ground Storage

(from Nirex [2002b])

Considerable R&D would be needed on store design and fuel packaging before long-term above ground storage could be implemented [Wilkinson et al 2002; Hill and Gunton 2001; Nirex 2002a]. It would be straightforward to make the safety case for storage for decades but much more difficult to do so for longer periods. Safeguards and security could be a major safety case issue.

Storage has on-going costs so funds would need to be established to maintain the storage facility in perpetuity. It is not possible to accurately quantify the total costs of indefinite storage and therefore its costs compared to other options can only be addressed by considering finite time periods [Wilkinson et al 2002] or by comparing the present estimated value of all future costs for the options. The capital costs of building a store would be much lower than those of building an underground repository, so over the first one or two centuries above ground storage would be much less expensive than underground disposal. Over thousands of years storage costs would exceed disposal costs, because of the continuing costs of store maintenance, safeguards, repair, replacement and insurance [Hill and Gunton 2001]. Storage costs do decrease at longer times because radioactive decay enables simpler store designs and fuel packages to be used [Nirex 2002a].

Above ground storage places responsibilities on future generations to monitor, maintain and replace stores. The option is not stable to socio-political changes such as new national funding priorities. Future generations would have direct control over the used fuel. In particular, it would be relatively easy to retrieve the fuel for treatment and/or for disposal if technical developments made existing options more attractive, or if new options became available [Hill and Gunton 2001]. Above ground storage would comply with all existing international treaties and conventions.

7. UNDERGROUND STORAGE

7.1 Description

Underground storage could take place in caverns or tunnels a few tens of meters beneath the earth's surface. The idea behind it is to provide security advantages and safety benefits in accident situations compared to surface storage, while retaining the ease of retrieval of the fuel [Wilkinson et al, 2002]. To date, only centralized underground stores have been considered.

The development of underground interim storage facilities for used nuclear fuel has not been widely practised, and most interim facilities are above ground. The best known example of an operating underground interim store is the CLAB facility in Sweden, where used fuel is stored in pools some 30 metres below the surface, prior to deep disposal in a repository yet to be constructed.

In 1998 the French government instructed the Atomic Energy Commission to examine the potential for development of a '*very long-term interim storage project*', involving either near-surface pools like CLAB or deeper, drift accessed facilities set in shallow hills. As many as ten of these concepts will be examined until 2006.

7.2 Summary of Assessments

Underground stores would be less vulnerable to external events (eg aircraft crash, missile attack) than above ground stores and would collapse more slowly if they fell into disrepair. Risks to the public and the environment from underground storage would therefore be lower than risks from above ground storage. Risks to workers could be greater, especially during construction and when the underground store underwent major refurbishment or was replaced [Hill and Gunton 2001].

Considerable R&D would be needed on store design before long-term underground storage could be implemented. One particular concern could be the method of cooling fuel. A water-cooled store might be the best initial option [Hill and Gunton 2001] but when the fuel has lost much of its heat an air-cooled store might be preferred. Alternatively long-term underground storage could be preceded by shorter-term above ground storage to allow fuel to cool. There would undoubtedly be difficulties in making the long-term safety case for underground storage but these would probably be less than those in making the case for long-term above ground storage.

Over a century or two the costs of underground storage would be greater than those of above ground storage but less than those of underground disposal. Over longer periods underground storage would be more expensive than underground disposal because of the on-going costs of store maintenance, safeguards, accident insurance and store replacement. Underground storage would become cheaper than above ground storage because underground stores would not have to be replaced as frequently as above ground buildings.

Underground storage places responsibilities on future generations to monitor, guard and maintain stores, and to replace them. The option is not as stable to socio-political changes as underground disposal but is more stable than above ground storage [Hill and Gunton 2001]. As in above ground storage, future generations would have direct control over the used fuel, and it would be relatively easy to retrieve the fuel for treatment and/or for disposal if technical developments made existing options more attractive or new options became available. Underground storage would comply with all existing international treaties and conventions.

8. INTERNATIONAL STORAGE

8.1 Description

This concept is essentially the same as above ground or underground storage, except that it takes place in another country. It is a relatively recent idea. Until the late 1990s there had never been any suggestion that used fuel or HLW, other than that awaiting reprocessing or repatriation, might be stored outside of the country of origin.

In April 1999 a US company, '*Non-Proliferation Trust Inc'*. (NPT) was established to pursue development of an international used nuclear fuel storage facility at Zheleznogorsk in Russia, with a lifetime of at least 40 years. The facility, which would be developed in an existing cavern in a hillside, would employ dry storage casks. A memorandum of understanding between NPT and the Russian nuclear ministry was signed in 2000.

8.2 Summary of Assessments

An international store could be above ground or below ground. In theory there are two cases to consider: one in which the store is in another country and one in which Canada hosts the international store. The latter option is not considered further here because it is outside of NWMO's mandate.

It is assumed that Canada would only be willing to send its used fuel to an international store if that store were in a politically stable country [Hill and Gunton 2001]. In such a case the advantages and disadvantages of international storage would be similar to those of above ground and underground storage (see Sections 7 and 8). There would be additional risks to the public and workers from transport of the fuel to the store. The risks to the public would be partly to the population of Canada and partly to people in other countries. The risks from storage itself would be mainly to the population in which the store is located.

There would be transport costs, which could be high if the store were in a country at a considerable distance from Canada. Presumably there would be initial payments for store construction and fuel emplacement, then regular payments for store operation, maintenance and replacement. Over long periods the option might be less expensive than above ground or underground storage in Canada [Hill and Gunton 2001]. Sending Canadian used fuel to an international store would not be against any international treaty but would contravene the self-sufficiency principle that is applied in radioactive waste management in most countries that have substantial nuclear programs.

9. UNDERGROUND DISPOSAL

9.1 Description

Underground or geological disposal in a deep repository is a long-term waste management option that is currently favored by many countries and by most international agencies [SAM 1996; NEA 1995; IAEA 2002; EC 2003]. It involves the use of the so-called '*multi-barrier system*', where combinations of engineered and man-made barriers (eg canisters, backfilling materials) are incorporated into the repository design, intended to prevent any water within the rock gaining access to the waste for thousands of years, during which time the waste would be cooling and the radioactivity decreasing by the process of radioactive decay. Repositories would be accessed by either shafts or inclined tunnels, which would be closed and sealed when all the waste had been emplaced. Construction and filling of a repository is expected to take several decades, perhaps longer in countries with large quantities of long-lived wastes.

The waste would be placed in suitable containers (stainless steel, copper, alloy); these would be placed in short vertical boreholes drilled down from the repository tunnel floor or placed horizontally on the floor and the tunnel backfilled. In each case, the waste would be surrounded by clay, bentonite or crushed rock. Emplacement would take place at depths ranging from 250-1500 metres [Allan and McMurry 1995], depending on the concept adopted and the host rock. Excavation of a deep underground repository using standard mining or civil engineering technology is likely to be limited to accessible locations (e.g. under land or near-shore) [Nirex 2002b]. Salt, clay, granite and volcanic tuff are among the rock types that are currently proposed for use in different countries because of the low groundwater flows through them.

In the original geological disposal concepts it was envisaged that the repositories would be backfilled and sealed as soon as possible after waste emplacement. Several countries are now adopting so-called '*staged disposal concepts*' where the decision to finally close and seal the repository will not be taken until many years into the future. During the time when the repository is open it would be monitored and the waste would be in state where it would be possible to retrieve it fairly easily should it prove necessary to do so. This allows confidence to be gained in the disposal method and allows decisions regarding final design and closure to be made in the light of experience gained during the life of a repository, rather than committing to a particular course of action right from the start [House of Lords Select Committee 1999; National Research Council 2003].

There are also concepts in which trial emplacements precede full-scale disposal. This is the plan in Sweden and is also under consideration in Switzerland. The Swiss EKRA study proposed a concept referred to as '*Monitored Long-term Geological Disposal*', comprising a test facility, a main facility and a pilot facility. The intention is to allow waste disposal to take place in the main facility while experiments are carried out in the test facility to make sure that the repository system is behaving as predicted. The pilot facility would be used as a demonstration of the disposal techniques being used, and would be kept open long after the closure of the main facility to confirm long-term performance [EKRA 2000].

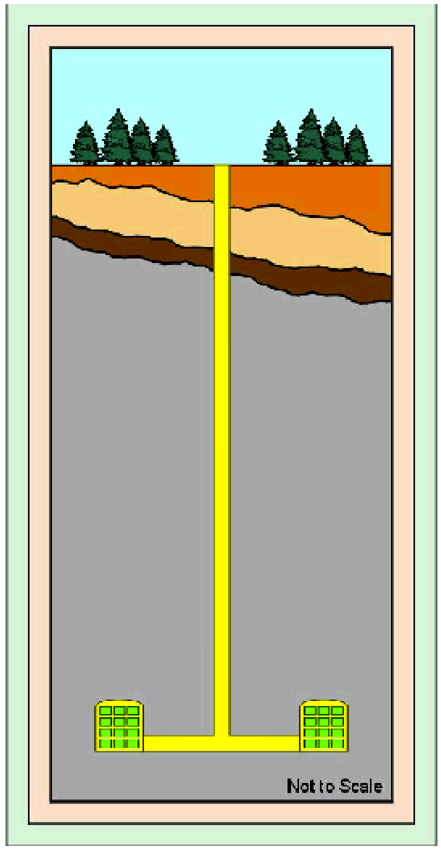

Figure 2 Artist's Impression of Underground Disposal

(from Nirex [2002b])

9.2 Summary of Assessments

As explained in Section 9.1, there are now two types of underground disposal concept that are being developed. One is the original concept in which the repository is sealed very soon after waste emplacement. The other is the concept in which the repository is kept open for some considerable time, with the waste in a monitored and retrievable state, until the decision is taken to close it. For ease of discussion, these two concepts are referred to here as 'early seal' and 'late seal' repositories (see Hill and Gunton [2001]).

Until the late seal repository is closed, its risks to the public and to workers would exceed those from an early seal repository (for example, because it is vulnerable to accidents such as fires and floods). After closure the risks from the two types of repository would be the same, provided that the late seal repository had been designed and operated so that its long-term safety was not compromised by the period in which it remains open [Hill and Gunton 2001; EKRA 2000]. Both types of repository would be sited and designed so that the most likely situation is that there would be no movement of radionuclides to the surface environment until hundreds of

thousands, or millions, of years after repository closure, and then radionuclide release rates would be very slow. Events that could lead to earlier or higher releases would have a low probability of occurring.
Safety cases for early seal repositories have been made in several countries. In most recent instances these cases have been subjected to international peer review by the radioactive waste management community and found to be sound. More R&D would be required in order to build a late seal repository than an early seal repository because the former concept is more recent and so less well-studied. The engineering equipment and techniques to build and close an underground repository largely exist. Much of the R&D needed would be investigation of candidate sites and development of site-specific designs.

In the shorter term an early seal repository would have lower costs, because the late seal repository is operated and actively guarded for longer. Long term costs for both types of repository depend on how much post-closure monitoring is envisaged and on whether it is thought desirable to have insurance or a contingency fund in case the monitoring reveals that something is going wrong. In principle, the insurance policy or contingency fund would be sufficient to cover retrieval of all the fuel [Hill and Gunton 2001].

Part of the rationale for underground disposal is that it places no responsibilities on future generations and that it is highly stable to adverse socio-political changes [EKRA 2000]. These features only exist for a closed repository and an early seal repository has advantages over a late seal repository in these respects [Hill and Gunton 2001]. On the other hand, in a late seal repository there would be a longer period in which it is relatively easy to monitor the fuel and retrieve it. Once any deep repository is closed retrieval will be technically possible but would be expensive and would entail risks to workers. Underground disposal in Canada would comply with all current international treaties, conventions and guidance.

10. INTERNATIONAL UNDERGROUND DISPOSAL

10.1 Description

The view has often been expressed that so-called regional facilities (most likely repositories) could help countries with relatively small nuclear programs, and consequently small volumes of used fuel requiring long-term management, and countries with no nuclear programs, and with only research, medical and industrial wastes to manage. Little has been done to encourage the development of such facilities and most of these countries have proceeded with a repository program whilst at the same time remaining open to solutions involving facilities in another country. In Switzerland, for example, the national disposal agency NAGRA considers it necessary to demonstrate that a suitable disposal site can be found in that country before actively seeking to participate in an international project.

A so-called '*international repository project*' was conceived in the early 1990s by an international organization known as '*Pangea*', funded by a number of organizations involved in waste management. The project was based on the conviction that the long-term containment of waste materials will be easier to achieve and to demonstrate in a simple, stable geological environment chosen using global rather than national considerations, without the restrictions imposed by political boundaries [McCombie et al 1999]. Using geological and climatic data, broad regions were identified in various countries as potentially able to provide optimal conditions for an underground repository. The natural geological safety barriers would, it was claimed, provide the main component of a safety case, thus avoiding the requirement for complex engineered solutions.

Pangea sought to identify and develop a so-called '*high isolation site*' for a repository capable of accepting used fuel and HLW from any country. It identified a potentially suitable site in Australia but there was considerable political opposition and the project was abandoned. Although Pangea itself ceased to exist in 2002, it was replaced by an organization known as the Association for Regional and International Underground Storage (ARIUS), which despite its name is also promoting regional and international disposal. Membership is open to organizations and individuals who support these aims. ARIUS is currently lobbying national and international bodies with a view to developing pilot facilities. At the present time this remains the only body actively pursuing international disposal, although a proposed Directive from the European Commission recommends that such options should be explored [EC 2003].

10.2 Summary of Assessments

As in Section 8, there are in theory two cases to consider: one in which the repository is in another country and one in which Canada hosts the international repository. The latter option is outside of NWMO's mandate and is not considered further here.

It is assumed that Canada would only be willing to send its used fuel to an international repository if that repository were in a politically stable country. In such a case the discussion in Section 9 is largely applicable [Hill and Gunton 2001]. There would be additional risks to the public and workers from transport of the fuel to the repository. The risks to the public would be partly to the population of Canada and partly to people in other countries. The risks from underground disposal itself would be mainly to the population in which the international repository is located. Depending on the site, these risks might be lower than for a repository in Canada [Wilkinson et al 2002].

There would be transport costs, which could be high if the repository were in a country at a considerable distance from Canada. Disposal costs would, presumably, be lower than if Canada had its own repository. Sending Canadian used fuel to an international repository would not be against any international treaty but would contravene the self-sufficiency principle that is applied in radioactive waste management in most countries that have substantial nuclear programs.

11. EMPLACEMENT IN DEEP BOREHOLES

11.1 Description

In this option, solid packaged wastes would be placed in deep boreholes drilled from the surface to depths of several kilometres with diameters of typically less than one metre [Nirex 2002b]. The waste containers would be stacked one on top of another in each borehole and would be separated from each other by a layer of bentonite or cement. The borehole would not be completely filled with wastes. The top two

kilometers would be sealed with materials such as bentonite, asphalt or concrete. It has been suggested for one concept that there could be a ring of sealed boreholes around the central disposal one [Khakhaev et al 1995].
This concept has been examined in a number of countries (eg Sweden, Finland, Russia) as a possible alternative to a deep repository. Boreholes could be drilled offshore as well as onshore in many types of rock, which expands the range of locations that could be considered for disposal using this concept.

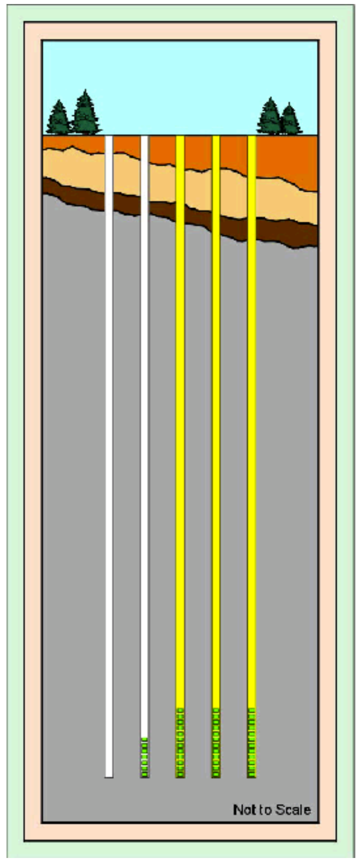

Figure 3 Artist's impression of Emplacement in Deep Boreholes

(from Nirex [2002b])

11.2 Summary of Assessments

The rationale for suggesting that radioactive waste could be emplaced in deep boreholes is that the long-term risks to people and the environment would be very low. A great deal of R&D would be required before the option could be implemented, for example to develop ways to characterize rocks at the required depth and to devise means to emplace the canisters of waste and to seal the boreholes [US National Research Council 2001; Autio et al 1996]. The option would be very expensive compared to underground disposal in a repository [Nirex 2002b; SAM 1996]. At present it is unclear whether ways could be devised to retrieve waste from deep boreholes. The option may be suitable for use in countries that have small quantities of long-lived waste to manage but it is not at present included in any major national R&D programs.

12. DIRECT INJECTION

12.1 Description

This option involves the injection of liquid radioactive waste directly into a layer of rock deep underground. The rock must be capable of minimizing any further movement following injection. In order to achieve this, a number of geological pre-requisites are required. There must be a layer of rock (the injection layer) with sufficient porosity (available space) to accommodate the waste and with sufficient permeability (connected space) to allow easy injection. This would allow the rock to act like a sponge. Above and below the injection layer there must also be impermeable layers that act as a natural seal [Nirex 2002b],

Although used for the disposal of liquid hazardous and LLW in the US in the past, this technique has only ever been used for liquid HLW in the former Soviet Union, at a number of locations, usually close to the waste generating sites. Direct injection requires detailed knowledge of subsurface geological conditions, as it does not incorporate any man-made barriers [Wilkinson et al 2002]. Used fuel would need to be converted to a liquid in order to use the option (eg by dissolving in acid, as in reprocessing).

12.2 Summary of Assessments

Direct injection would give rise to higher long-term risks to people and the environment than underground disposal of solid fuel because in direct injection there are no ‘barriers’ to radionuclide movement other than the rock [Wilkinson et al 2002]. It could be difficult to find a suitable site for the injection because geological formations that are permeable enough to take the dissolved fuel tend not to have the ability to isolate it from the biosphere, and may be associated with hydrocarbon or water resources [SAM 1996]. It would be important to locate the fuel dissolution plant at the injection site so as to avoid transport of highly active liquid waste.

Implementation of direct injection would involve a great deal of research into candidate geological formations and it would take much effort to make the long-term safety case [Wilkinson et al 2002; SAM 1996]. The option could be inexpensive to implement compared to underground disposal of solid fuel [Wilkinson et al 2002]. There would be no control of the fuel after disposal and it would not be possible to retrieve it. Although the option would not contravene international conventions it would not be consistent with the spirit of international guidance on the long-term management of radioactive wastes.

In summary, published assessments indicate that direct injection offers no substantial advantages, other than short-term financial ones, over underground disposal of intact solid fuel and has some significant disadvantages. It is not being pursued in any country as a means of dealing with an entire national inventory of used nuclear fuel.

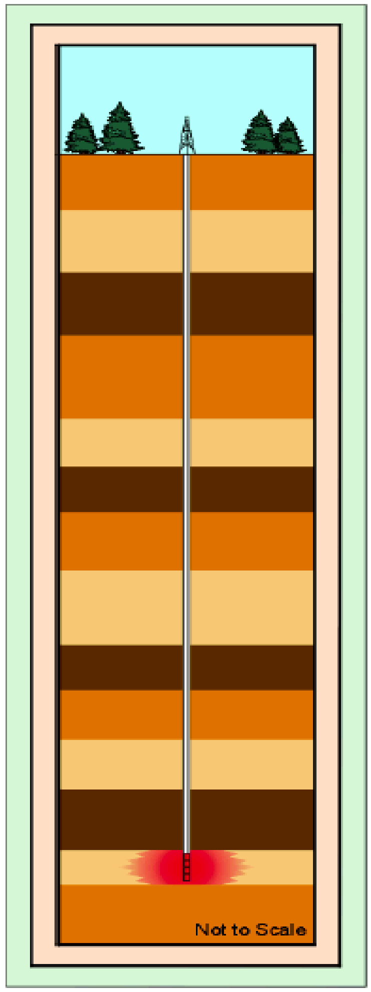

Figure 4 Artist's impression of Direct Injection

(from Nirex [2002b])

13. ROCK MELTING

13.1 Description

This option involves the melting of wastes into rock at depth using the heat-generating capacity of the waste. The waste in liquid or solid form could be placed in an excavated cavity or a deep borehole [Nirex 2002b]. The heat generated by the wastes would then accumulate resulting in temperatures great enough to melt the surrounding rock and dissolve the radionuclides in a growing sphere of molten material. As the rock cools it would crystallize and incorporate the radionuclides in the rock matrix, thus dispersing the waste throughout a larger volume of rock. There are variations in which the heat generating waste would be placed in containers; the rock around the containers would melt thus sealing the waste in place.

Research was carried out on this option in the late 1970s and early 1980s, when the option was taken forward to the engineering design stage (see Milnes [1985] and Nirex 2002b]). The design involved a shaft or borehole which led to an excavated cavity at a depth of 2-5 kilometres. It was estimated, but not demonstrated, that the waste would be immobilized in a volume of rock one thousand times larger than the original volume of waste. Another early proposal was to use weighted containers of heat-generating wastes that would continue to melt the underlying rock, allowing them to move downwards to greater depths with the molten rock solidifying above them.

There was renewed interest in this option in the 1990s in Russia, particularly for the disposal of limited volumes of specialized waste such as plutonium [Nirex 2002b]. A scheme was proposed in which the waste content of the container, the container composition and the placement layout would be designed to preserve the container and prevent the wastes becoming incorporated in the molten rock. The host rock would be only partially melted and the container would not move to greater depths. According to Nirex, Russian scientists have also proposed that HLW, particularly excess plutonium, could be placed in a deep shaft and immobilized by a nuclear explosion, which would melt the surrounding rock.

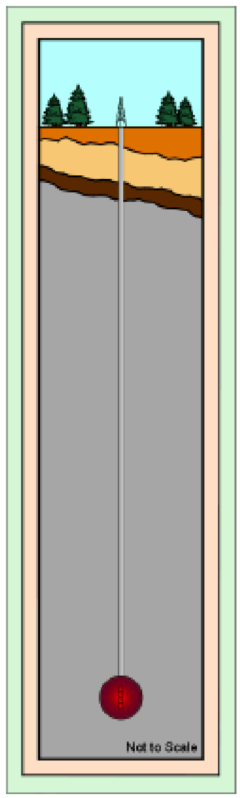

Figure 5 Artist's impression of Rock Melting

(from Nirex [2002b])

13.2 Summary of Assessments

There have been no practical demonstrations that rock melting is feasible so there would be much R&D to do before the option could be implemented [Nirex 2002b]. The option would have relatively high operational risks because of the need to work with 'hot' fuel (so that it would melt the rock) [Nirex 2002a]. It would be difficult to make the long-term safety case for the option because of uncertainties about the shape and properties of the rock mass in which the fuel is dispersed [SAM 1996].

The financial costs of rock melting could be higher than those of underground disposal of packaged fuel [SAM 1996]. There would be no control of the fuel after disposal and it would not be possible to retrieve it. The option is not being investigated in the national program of any country.

14. DISPOSAL AT SEA

14.1 Description

This option consists of placing packaged waste on the bed of the deep ocean. The packaging would consist of canisters that are designed to last for a thousand years or more and the waste would be in a solid form that would release radionuclides into the ocean very slowly when the canisters fail. The site would be one where the water is a few kilometres deep, so that the waste would not be disturbed by human activities and so there would be substantial dilution of radionuclides before they reach the surface environment. It was also suggested that the waste canisters could be placed in concrete boxes, for added protection and ease of monitoring.

Sea disposal was investigated by the Nuclear Energy Agency's Seabed Working Group but not in the same detail as sub-seabed disposal (see Section 15). It would be an extension of the 'sea dumping' method that was used for disposal of solid low level radioactive waste until the early 1980s and that is now prohibited under international conventions.

14.2 Summary of Assessments

Disposal on the bed of the deep ocean would pose low health risks to individual people but would result in radioactive contamination of large sections of the global marine environment (albeit at low levels). R&D would be required on the design of containers for the fuel and on methods of retrieval of containers from deep waters [Wilkinson et al 2002]. There would be very little control of the fuel after disposal. Sea disposal is prohibited by international conventions and is not now included in any national or international R&D programs.

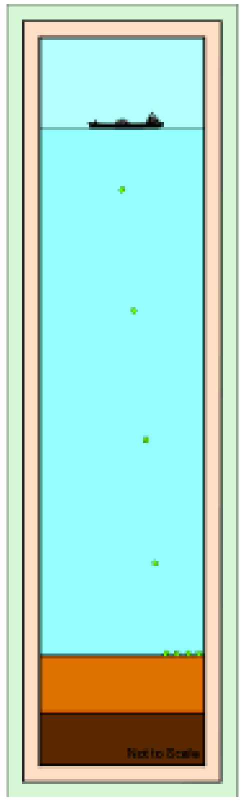

Figure 6 Artists impression of Disposal at Sea

(from Nirex [2002b])

15. SUB-SEABED DISPOSAL

15.1 Description

In this option, radioactive waste containers would be buried in a suitable geological setting beneath the deep ocean floor. Sub-seabed disposal was investigated extensively in the 1980s, primarily under the auspices of the Seabed Working Group set up by the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development [NEA 1988]. Canada participated in this group, as did the US, the UK, Japan and several European countries.

The main sub-seabed disposal method involves the use of ‘penetrators’. These are missile-shaped canisters that hold the solid waste. They would be dropped from ships and would bury themselves to a depth of a few metres or more in the sediments on the ocean floor. The disposal sites would be ones where the sediments are plastic and have a high capacity to absorb radionuclides, and where the water is a few kilometres deep. The idea behind the concept is that the waste form, inner canister, penetrator and sediments would all ensure that release of radionuclides into the ocean does not begin for thousands of years or more and even then occurs very slowly, and that there would be substantial dilution when release does finally occur.

It has also been suggested that wastes could be emplaced in the deep ocean floor using drilling equipment based on the techniques that have been in use in deep sea oil exploration and geological research for about 30 years. In this method, stacks of waste packages would be placed in holes drilled to a depth of 800 metres, with the uppermost container about 300 metres below the seabed.

Research on sub-seabed disposal effectively ceased in the late 1980s and early 1990s when it became clear that there would always be intense political opposition to it. Some marine scientists are still interested in it [eg Hollister and Nadis 1998].

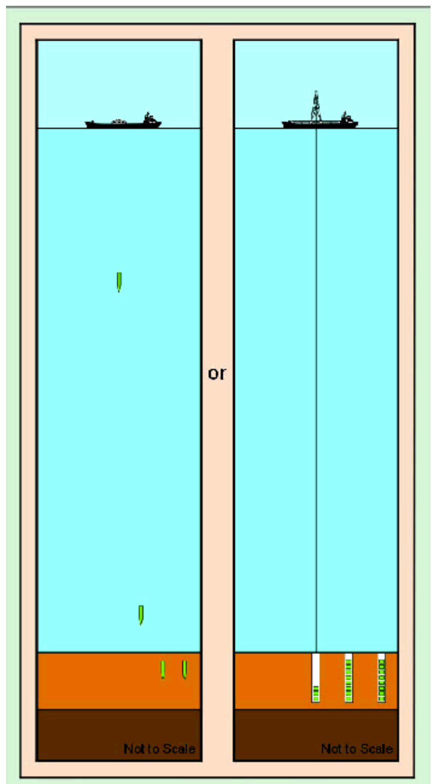

Figure 7 Artist's impression of Sub-Seabed Disposal

(from Nirex [2002b]

15.2 Summary of Assessments

If the fuel is emplaced using penetrators, sub-seabed disposal would pose low risks to individual people. Levels of contamination of the marine environment would also be low, provided that the holes above the penetrators close. Placing the fuel in boreholes drilled in the bed of the deep ocean would pose lower long-term risks than using penetrators [Wilkinson et al 2002]. R&D would be required on sediment properties and hole closure, but an outline safety case for sub-seabed disposal has already been made [Allan and McMurry 1995]. Retrieval of fuel after sub-seabed disposal would be extremely difficult. Like sea disposal, sub-seabed disposal is prohibited by international conventions and is not now included in any national or international R&D programs.

16. DISPOSAL IN ICE SHEETS

16.1 Description

For this option containers of heat-generating waste would be placed in very thick stable ice sheets, such as those found in Greenland and Antarctica. There are three main potential concepts, which are as follows [Allan and McMurry 1995; Wilkinson et al 2002].

1. In the meltdown concept the containers would melt the surrounding ice and be drawn deep into the ice sheet, where the ice would refreeze above the wastes creating a thick barrier.

2. In the anchored emplacement concept, the containers would be attached by surface anchors that would limit their penetration into the ice by melting to around 200-500 metres, thus enabling possible retrieval for several hundred years before surface ice covers the anchors.

3. In the surface storage concept, the containers would be placed in a storage facility constructed on piers above the ice surface. As the piers sank, the facility would be jacked up to remain above the ice for perhaps a few hundred years. Then the entire facility would be allowed to sink into the ice sheet and be covered over.

16.2 Summary of Assessments

There has been very little work on disposal in ice sheets because there has never been enough confidence about predicting the fate of the waste and because of the potential for release of radionuclides into the ocean [House of Lords Select Committee 1999; Wilkinson et al 2002; Allan and McMurry 1995]. The two principal candidate sites for the option would be Antarctica and Greenland. Disposal of radioactive waste in Antarctica is prohibited by international treaty and Denmark has indicated that it would not allow such disposal in Greenland [Nirex 2002b]. Disposal in ice sheets is not included in any national or international R&D programs.

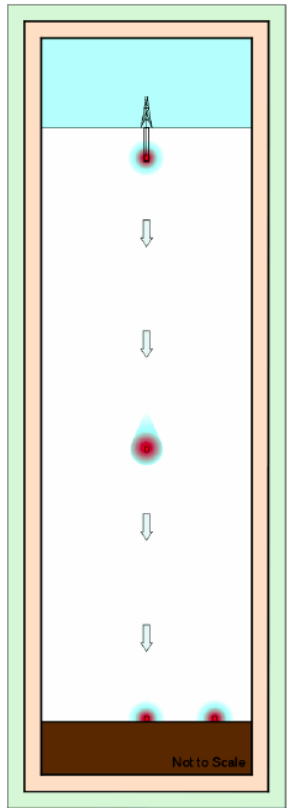

Figure 8 Artist's impression of Disposal in Ice Sheets

(from Nirex [2002b])

17. DISPOSAL IN SUBDUCTION ZONES

17.1 Description

This option was initially proposed in the 1980s. There are two main types of subduction zone. One where denser sections of oceanic plate are being moved towards and underneath sections of less dense continental plate, and another in which an older oceanic plate descends below a younger one. The downward movement is marked by an offshore trench, and earthquakes occur adjacent to the inclined contact between the two plates. In some cases the edge of the overriding plate can be crumpled and uplifted to form a mountain chain parallel to the trench. Deep sea sediments may be scraped off the descending plate and incorporated into the adjacent mountains. As the plate descends into the hot mantle parts of it may begin to melt. The magma thus formed migrates upwards, some of it reaching the surface as lava erupting from volcanic vents. The idea for this concept would be to dispose of wastes in the trench region, such that they would be drawn deep into the Earth [Nirex 2002b].

As subduction zones are invariably offshore, this concept can also be considered as a variant of emplacement in the sea or beneath the seabed (see Sections 14 and 15). Either tunneling or deep sub-seabed boreholes could theoretically be used to emplace the waste close to an active subduction zone [Wilkinson et al 2002]. Free-fall penetrators, as proposed for the sub-seabed option, could also be used.

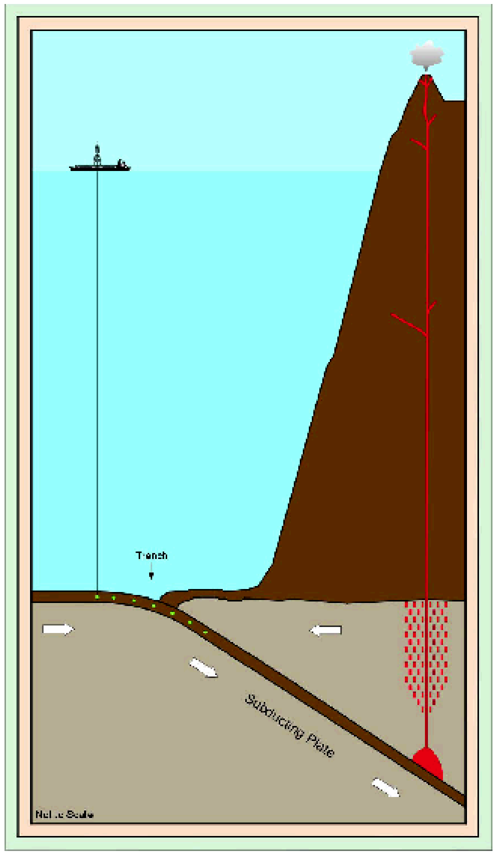

Figure 9 Artist's impression of Disposal in a Subduction Zone

(from Nirex [2002b])

17.2 Summary of Assessments

Lack of confidence in predicting the fate of the wastes has also been the reason why little attention has been paid to disposal in subduction zones [House of Lords Select Committee 1999]. Concerns have been expressed that waste might return to the surface environment via volcanic eruptions [EKRA 2000]. It has also been suggested that the option would be seen as a form of sea disposal and hence would be prohibited by international conventions [Nirex 2002b]. Retrieval of the fuel after disposal in a subduction zone would be impossible. The option is not included in any national or international R&D programs.

18. DISPOSAL IN SPACE

18.1 Description

The objective of this option is to remove the radioactive waste from the Earth, for all time, by ejecting it into outer space. A rocket or space shuttle would be used to launch the packaged waste into space [Nirex 2002b]. There are several ultimate destinations for the waste that have been considered, including directing it into the Sun, leaving it in an orbit around the Sun between Earth and Venus and ejecting it from the solar system altogether. One of these variants would be necessary because placing the waste in space in a near-Earth orbit would not be sufficient due to the possibility of it returning to Earth while it was still highly radioactive. It has been suggested that the option would be most suitable for small volumes of the most toxic waste [National Research Council 2001].

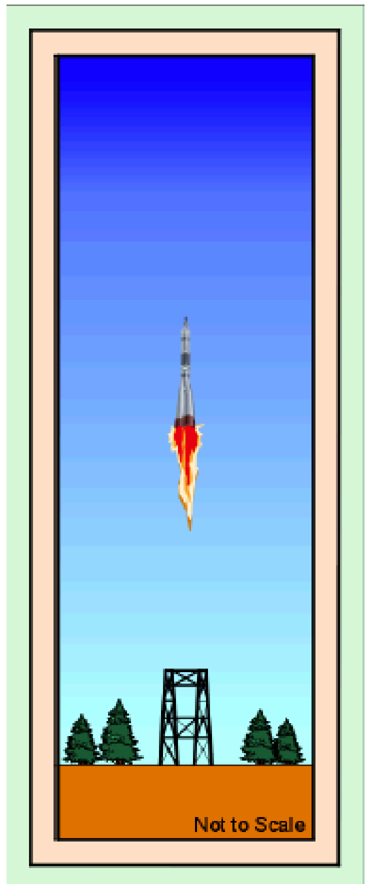

Figure 10 Artist's impression of Disposal in Space

(from Nirex [2002b])

18.2 Summary of Assessments

Disposal of radioactive wastes in space has never been included in any major R&D programs because of the high radiological consequences of an accident during launching of the space vehicle [House of Lords Select Committee 1999; Wilkinson et al 2002]. The option would also be extremely expensive for large quantities of waste [Wilkinson et al 2002; Nirex 2002b; SAM 1996; Allan and McMurry 1995; POST 1997]. Opposition to disposal in space was reinforced by the Challenger accident (and has probably been reinforced again by the Columbia disaster).

19. DILUTE AND DISPERSE

19.1 Description

Dilute and disperse differs from all the other storage and disposal options in that there is no element of containment of the waste and isolation from the environment. It has never seriously been proposed for used fuel or reprocessing HLW but it is included in this review for completeness.

In order to implement dilute and disperse for used fuel it would be necessary to dissolve the fuel in acid and neutralize the solution. It could then be discharged slowly down a pipeline into the sea. The discharge site and rate would be such that radiation doses to people never approach or exceed internationally accepted limits. Another possibility would be to transport the fuel solution by tanker to the open ocean and release it there, although this might be prohibited under international conventions.

19.2 Summary Assessment

This option has the potential to give rise to relatively high health risks if there is an accident in which the fuel discharge rate is high. Dilute and disperse would lead to significant contamination of the marine environment near the discharge point and lower levels of contamination over a much wider area. It could be difficult to make the safety case for dilute and disperse via slow discharge down a pipeline and via tanker transport to the open ocean. The latter option would probably be prohibited by international conventions and any dilute and disperse method for used fuel would be against the spirit, if not the letter, of international guidance. No estimates have been made of the option’s costs.

20. CONCLUSIONS

Based on the results of published assessments, as summarized in Sections 4-19, it is suggested that the options for the long-term management of used nuclear fuel can be placed in three categories for the purpose of determining R&D priorities:

- those of considerable interest
- those of some interest
- those of very little interest.

The suggested assignment of the options to these categories is shown in Table 2.

The assignment of options to the ‘*considerable interest*’ category follows directly from the discussion in Sections 4-19. The options in this category are being assessed in detail or implemented in many national programs.

Options in the ‘*some interest*’ category are part of some national programs or may be assessed in detail in future in some countries. Partitioning and transmutation (P&T) is included in the ‘*some interest*’ category rather than the ‘*considerable interest*’ category because, although it is under investigation in several countries, it is not a complete management option for used fuel and could not be implemented soon (see Section 4). It is recognized internationally that the possibility that P&T could become a readily available and very attractive treatment option in several decades time could be a reason for choosing storage rather than disposal.

Table 2 Suggested Categorization of Management Options

Considerable interest	Some interest	Very little interest
Above ground storage Underground storage Underground disposal	Partition and transmutation Reprocessing International storage International underground disposal	Emplacement in deep boreholes Direct injection Rock melting Disposal at sea Sub-seabed disposal Disposal in ice sheets Disposal in subduction zones Disposal in space Dilute and disperse

Reprocessing is placed in the '*some interest*' category because it is in use in some countries (especially France and the UK) but there are no countries that intend to take it up for civil waste management purposes alone (see Section 5). International storage and international disposal (see Sections 8 and 10) are placed in the '*some interest*' category because there might be international developments over the next few years that would make them more practicable and desirable than they appear now, at least for some countries.

The options in the '*very little interest*' category have been investigated to varying extents since the early 1970s. These options are still advocated by a few organizations and individuals but are not now part of any national R&D or implementation programs.

21. REFERENCES

Allan CJ and J McMurry 1995; '*Disposal Concepts and Disposal Alternatives'.* In: *'Requirements for the safe management of radioactive waste'*; Proceedings of a seminar held in Vienna, 28-31 August 1995. IAEA-TECDOC-853 December 1995

Autio J et al 1996; '*Assessment of alternative disposal concepts*'. Posiva-96-12. December 1996

Bradley DJ 1997; '*Behind the Nuclear Curtain: Radioactive Waste Management in the Former Soviet Union*'. DR Payson (Ed). Publ. by Battelle Press

Bunn M et al 2001; '*Interim Storage of Spent Nuclear Fuel: A safe, flexible and cost-effective near-term approach to spent fuel management*'. A Joint Report from the Harvard University Project on Managing the Atom and the University of Tokyo Project on Sociotechnics of Nuclear Energy. June 2001.

Cummings R et al 1996a; '*An Assessment of Partition and Transmutation against UK Requirements for Radioactive Waste Management'*. Department of Environment report DOE/RAS/96.007. DOE, London

Cummings R et al 1996b; '*An Assessment of Partition and Transmutation against UK Requirements for Radioactive Waste Management: Supporting Studies'*. Department of Environment report DOE/RAS/96.010. DOE, London

EKRA 2000; '*Disposal Concepts of Radioactive Waste'* - Final Report. EKRA - Expert Group on Disposal Concepts for Radioactive Waste, Federal Office of Energy, CH-3003 Bern, Switzerland, 31st January 2000

European Commission 2003; '*Draft proposal for a COUNCIL DIRECTIVE (Euratom) on the management of spent nuclear fuel and radioactive waste'*. Published November 2002, approved January 2003

Hill M and Gunton M 2001; '*A Multi-Attribute Comparison of Indefinite Storage and Geological Disposal of Long-Lived Radioactive Wastes'.* Pangea Resources International Technical Report, PTR-01-02 January 2001

House of Lords Select Committee on Science and Technology 1999; '*Management of Nuclear Waste*'. HL paper 41, March 1999. (See also the written and oral evidence to the committee in HL paper 89 Session 1997-1998 and HL paper 26 Session 1998-1999.)

International Atomic Energy Agency 1997; *Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities.* Proc. Int. Symp. Vienna, 3-6 June 1997. Vienna, IAEA

International Atomic Energy Agency 2002; *'Issues relating to safety standards on the geological disposal of radioactive waste'*. Proceedings of a specialists' meeting held in Vienna, 18-22nd June 2001. TecDoc-1282

Khakhaev B et al 1995. *Problem of highly active waste disposal*. In Proc. 5th International Conference on Radioactive Waste Management and Environmental Remediation, ICEM'95. Berlin, 4-8 September 1995. Vol. 1 p705.

McCombie C et al 1999; '*The Pangea International Repository: A Technical Overview'*. In: Proceedings of Waste Management '99. Tucson, AZ. 1999

Milnes AG 1985; '*Geology and Radwaste'*. Academic Press Inc. London

Nuclear Energy Agency 1988; '*Feasibility of Disposal of High Level Radioactive Waste into the Seabed (Vols 1-8)'*. OECD, Paris

Nuclear Energy Agency 1995; '*The Environmental and Ethical Basis of Geological Disposal*'. A Collective Opinion of the NEA RWMC. Published by OECD, Paris

Parliamentary Office of Science and Technology 1997; '*Radioactive waste – Where Next?'*

QuantiSci Ltd 1999; '*An R&D Strategy for the Disposal of High-Level Radioactive Waste and Spent Nuclear Fuel'*. TSO, London, DETR/RAS/099.016

SAM Ltd 1996; '*An International Comparison of Disposal Concepts and Postclosure Assessments for Nuclear Fuel Waste Disposal*'. TR-M-43 Prepared for AECL.

United Kingdom Nirex Limited 2002a: '*Options for Radioactive Management that have been Considered by Nirex'*. Nirex Report N/049, May 2002.

United Kingdom Nirex Limited 2002b; '*Description of Long-term Management Options for Radioactive Waste Investigated Internationally'*. Nirex Report N/050, May 2002

US National Research Council 2001; '*Disposition of High-Level Waste and Spent Fuel; The Continuing Societal and Technical Challenges'*. National Academy Press, Washington, D. C. 2001

US National Research Council (Board on Radioactive Waste Management) 2003; '*One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste*'. National Academy Press, Washington, D. C. 2001

Wilkinson P, Warren L and Butler G 2002; '*Identification of Information Needed to Decide with Confidence on the Long Term Management of Options for Long Lived Radioactive Waste'.* DEFRA Report No: DEFRA/RAS/02.014. Prepared by Wilkinson Environmental Consultants.