Storage and Disposal of Spent Fuel and High Level Radioactive Waste

A. Introduction

1. Although different types of reactors have different types of fuel, the descriptions in this summary are, for simplicity, based primarily on the fuel used in light water reactors (LWRs). Most of the procedures and conclusions also apply to other types of reactor fuel.

2. Nuclear fuel consists of fuel pins that are stacks of uranium oxide or mixed uranium plutonium oxide (MOX) cylindrical ceramic pellets, with diameters of 8–15 mm, that are encapsulated in metallic tubes. The fuel pins are grouped together in fuel assemblies. Each fuel assembly can be handled as a single entity, thus simplifying the fuelling and defuelling of reactors and the subsequent handling of spent nuclear fuel.

3. The useful life of a fuel element in the core of an operating reactor is usually 3–7 years. By the time it is removed from the core it is highly radioactive and generates both heat and radiation, primarily gamma radiation and neutrons. The fuel elements are therefore handled and stored under water, which provides both the necessary cooling and necessary radiation shielding. Over time both the radioactivity and the cooling requirements decrease. The minimum period for storing spent fuel under water is 9–12 months, after which cooling requirements have usually dropped enough that dry storage can be considered. Shielding requirements, however, remain for thousands of years.

4. The spent fuel is 95–96% uranium with an enrichment level at or slightly above that of natural uranium, 1% plutonium, 0.1% other actinides and 3–4% fission products. The uranium and plutonium can potentially be reused for new nuclear fuel.

5. Two different management strategies are used for spent nuclear fuel. In one the fuel is reprocessed to extract usable material (uranium and plutonium) for new fuel. In the other, spent fuel is simply considered a waste and is stored pending disposal. If the spent fuel is to be reprocessed, it is shipped to a reprocessing facility where the fuel elements and fuel rods are chopped into pieces, the pieces are chemically dissolved, and the resulting solution is separated into four basic outputs: uranium, plutonium, high level waste (HLW), and various other process wastes. In terms of cooling and shielding, the HLW, which contains fission products and actinides, needs to be handled similarly to spent fuel of the same age.

6. As of today, France, Russia, Japan, India and China reprocess most of their spent fuel, while the USA, Canada, Finland and Sweden have currently opted for direct disposal.[1] Most countries have not yet decided which strategy to adopt. They are currently storing spent fuel and keeping abreast of developments associated with both alternatives.

[1] In February 2006 the USA announced a Global Nuclear Energy Partnership, which includes the development of advanced recycling technologies for use in the USA.

B. Spent Fuel Storage

7. Regardless of the strategy chosen, spent fuel management always involves a certain period during which the spent fuel is stored.

- For initial cooling and shielding, all spent fuel needs to be stored under water in storage pools at the reactor facility directly after its removal from the reactor and prior to being transported off-site. This initial storage period lasts a minimum of 9–12 months to allow both the radiation level and heat level to decay sufficiently. In most cases spent fuel is stored in these on-site pools for several years, and sometimes up to tens of years, depending on the storage capacities of the pools.
- If the fuel is to be reprocessed, it is transported to a reprocessing facility and stored there in buffer storage pools before being fed into the process. Modern reprocessing plants have large buffer storage capacities.
- Fuel not destined for reprocessing remains stored in the original reactor storage pools or is transported to separate 'away from reactor' (AFR) fuel storage facilities. Despite their name, these AFR facilities may be either on a part of the reactor site or at other dedicated sites. Currently there are around 90 operating commercial AFR spent fuel storage facilities around the world, most of them being dry storage facilities at reactor sites.

8. There are two storage technologies in use today: wet storage in pools or dry storage in vaults or casks. There are now more than 50 years of experience with wet storage of spent fuel in water pools. Figure 1 shows the pool at the CLAB wet storage facility in Sweden. Wet storage is a mature technology, and likely will continue to be used for many years. However, as delays are incurred in implementing plans for geologic repositories and for reprocessing, storage of spent fuel for extended durations of several decades is becoming a reality. This trend of more storage for longer durations is expected to continue, and some countries are now considering storage periods of 100 years or more. While no significant problems are anticipated with extended wet storage, it is important to monitor these facilities, learn from experience and apply the results in designing and operating newer facilities, from the beginning, for extended storage.

Figure 1. The pool at the CLAB wet storage facility in Sweden.

9. Dry spent fuel storage is a younger technology that has developed substantially over the past twenty years. It is more limited in heat dissipation capability than wet storage, but has the advantage

of being modular, which spreads capital investments over time, and, in the longer term, the simpler passive cooling systems used in dry storage reduce operation and maintenance requirements and costs. Dry storage facilities use a variety of configurations including modular vaults, silos and casks. Figure 2 shows the casks at the ZWILAG facility in Switzerland and the Fort St. Vrain vault in the USA.

Figure 2. Dry fuel storage technologies: casks at the ZWILAG facility in Switzerland (left) and the Fort St. Vrain vault in the USA (right).

C. Spent Fuel Arisings and Future Issues

10. From today's 441 operating nuclear power plants in 30 countries, over 10 000 metric tons of heavy metal (tHM) are unloaded each year, with annual discharges projected to increase to ~11 500 tHM by 2010. Since less than one third is reprocessed, an additional 8 000 tHM/year, on average, will need to be placed in storage facilities.

11. The total amount of spent fuel generated worldwide in the 52-year history of civilian nuclear power is over 276 000 tHM, of which roughly one third has been reprocessed, leaving around 190 000 tHM of spent fuel, mostly in wet storage pools but with an increasing amount in dry storage. Figure 3 shows how the amounts of spent fuel generated, reprocessed and stored around the world have evolved since 1990, and includes projections through 2020 based on a reference scenario lying between the high and low projections reported in Section A.2. The total cumulative amount of spent fuel that will be generated by 2020 is estimated at 445 000 tHM, of which about 324 000 tHM will still be in storage rather than recycled.

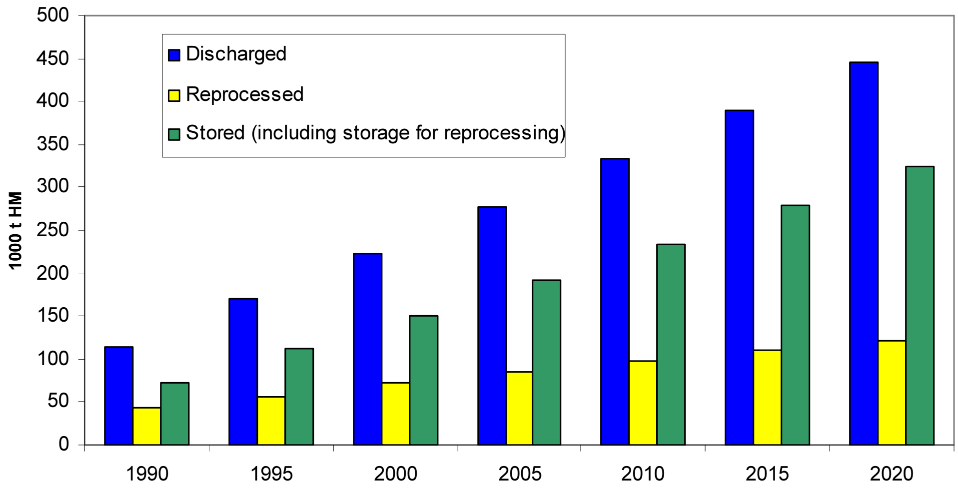

Figure 3. Historical and projected amounts of spent fuel discharged, reprocessed and stored.

12. Based on now more than 50 years of experience with storing spent fuel safely and effectively, there is high confidence in both wet and dry storage technologies and their ability to cope with the rising volumes shown in Figure 3. However, increasing storage inventories, extended storage periods and the evolution of reactor designs and operating practices mean that the engineering and management of storage facilities must also evolve. Increased inventories and extended storage periods mean, first, a need for more capacity and for assuring that facilities are designed and operated, or upgraded, for longer term storage. Second, the long term integrity of the fuel must be assured for its long term storability and retrievability. Third, storage facilities must be successively adapted to new and evolving fuel designs, e.g. the current trends toward use of MOX fuel and higher fuel burnups (and corresponding higher enrichment levels in fresh fuel). None of today's trends promise great difficulties for evolving storage technology. Some, for example the trend towards applying burnup credit (i.e. removing the assumption that stored fuel has the same reactivity as fresh fuel) create the potential for increasing the amount of spent fuel stored in a given space, thereby reducing the need for new capacity, reducing costs and reducing operational exposure.

D. Storage of High Level Waste

13. Liquid high level waste (HLW) from the reprocessing of spent fuel is first solidified directly at the reprocessing facility. The most frequently used solidification process is vitrification, i.e. the waste products are melted together with glass material at high temperatures such that they are incorporated into the glass structure. The melted mixture is poured into stainless steel containers, and, after controlled cooling, these are sealed by welding and then decontaminated to remove possible surface contamination. To give a specific example, at COGEMA's La Hague reprocessing plant in France, HLW is calcinated, mixed with borosilicate glass powder and melted in an induction furnace at 1100ºC. The steel canisters into which the melted mixture is poured are 1.34 m long and 0.43 m in diameter. One canister can hold the HLW from 1.3 tHM of reprocessed spent fuel.

14. Special storage facilities have been built for these HLW containers at spent fuel reprocessing plants. The containers must be continually cooled to avoid thermal stress and to prevent possible changes in the glass structure. Depending on how much heat is generated, stored containers can be cooled by natural or forced air convection. Any air used for cooling is filtered to remove possible contamination before being exhausted to the general environment. Dry storage can ensure the integrity and safety of vitrified HLW for extended storage periods (i.e. more than 50 years) while geological repositories are being developed.

15. Figure 4 shows the storage hall for vitrified waste at La Hague. Canisters are stored in vaults, each with a number of channels, the round tops of which are visible in the picture. Each channel can hold up to twelve canisters stacked on top of each other. The storage facilities are modular, so that they can be extended as the need arises, and very compact. The technology used permits storage of all vitrified waste from 50 years' operation of France's 59 nuclear power plants on an area the size of a rugby field.

Figure 4. The storage hall for vitrified waste at La Hague.

E. Disposal of Spent Fuel and High Level Waste

E.1. Guiding Principles

16. The main characteristics governing spent fuel and high level waste disposal are the long-lived radioactivity content of the spent fuel or HLW, its heat generation and its radiation level. The heat generation limits the amount of waste that can be disposed of in a given volume of rock. High radiation levels require that all waste handling is shielded and/or uses remote handling systems. And the amount of long-lived radioactivity means that the safety of a repository is an issue that must be considered looking forward for tens to hundreds of thousands of years.

17. The fundamental design objective of geological repositories is to confine the waste and to isolate it from the environment. Adequate long-term safety must be provided without reliance on active controls or ongoing maintenance. Geological repositories are therefore designed to be passively safe, such that continued indefinite institutional control is not required to assure safety. Nonetheless institutional control will likely be maintained for a long initial period to provide additional reassurance and to comply with current safeguards and security requirements, issues that have received increasing attention in recent years.

18. General guiding principles can be found in the multilateral legal instruments adopted under the Agency's auspices, in particular the Convention on the Physical Protection of Nuclear Material and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. With respect to guiding principles specifically for the disposal of spent fuel and high level waste, a more detailed discussion is also available in the safety series published by the Agency.[2]

E.2. Technical Principles and Solutions

19. To comply with the guiding principles described above, all countries with well developed disposal concepts incorporate the following basic technical principles in their national approaches:

- encapsulation of spent fuel or HLW in a tight canister with a very long expected lifetime;
- assurance that the conditions in the repository will allow the canister to remain intact and tight for as long as possible (such conditions include, for example, mechanical stability, stable geochemical conditions and very limited ground water movement that could bring corrosive agents in contact with the canisters); and
- backfilling of the repository with appropriate materials and locating it in geological media that, together with the backfill, strongly limit water movement and, eventually, waste movement when the integrity of the canisters finally breaks down.

20. Technical solutions reflecting all three of these principles are already available today, although all will likely be continually improved and refined to take advantage of new technical advances in waste management and materials technologies. Figure 5 shows the multi-barrier concept for spent fuel disposal in Sweden. It has barriers at three levels. First is the waste matrix and initial waste package. In the Swedish case, the solid fuel pellets and fuel-rod cladding provide barriers at this level. Second are engineered barriers, i.e. the copper canister with a cast iron insert, surrounded by compacted bentonite (Figure 5). Third is the host formation, e.g. the extensive crystalline bedrock in Figure 5.

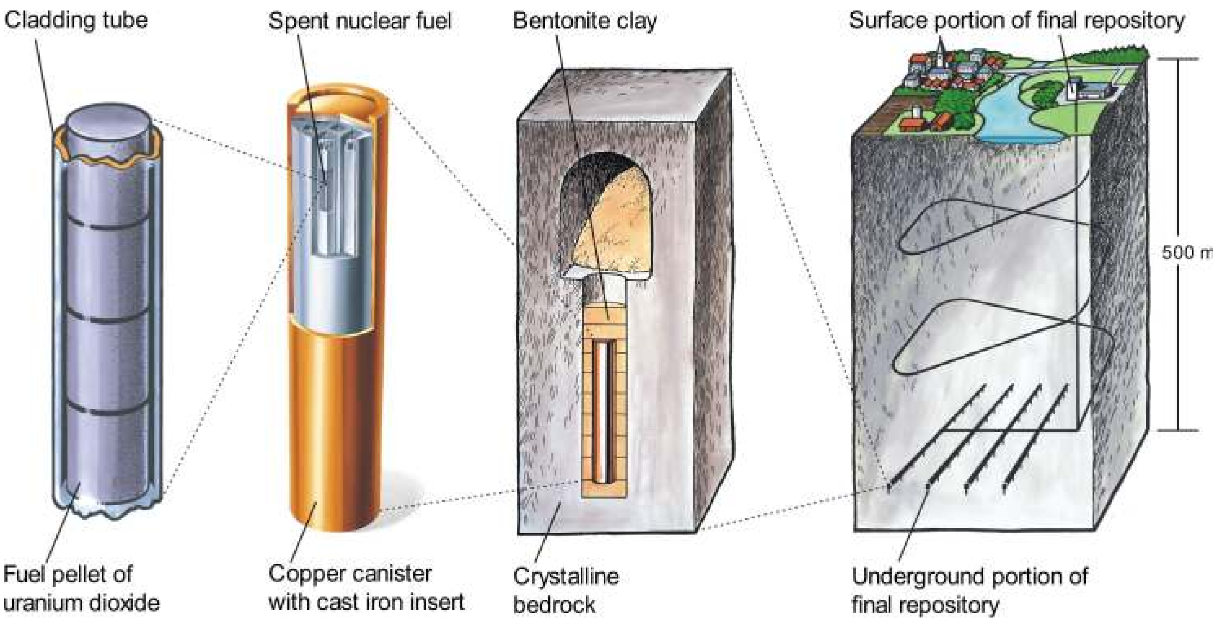

Figure 5. The Swedish concept for the disposal of spent nuclear fuel as an illustration of the multi-barrier concept.

[2] http://www-ns.iaea.org/standards/

E.3. Implementation

21. No geological repository for spent fuel or HLW has yet been built. The only operating geological repository to date is the Waste Isolation Pilot Plant (WIPP) in the USA. Since its start-up in 1999, WIPP has been disposing of low level transuranic (long-lived) radioactive waste generated by research and the production of nuclear weapons. In addition to WIPP, good progress has been made in several countries (discussed below) on repositories for HLW or spent fuel from commercial nuclear power plants. However, none is expected to start operation until around 2020.

22. Only two countries, Finland and the USA, have settled on sites for their geological repositories. Sweden has narrowed its candidate sites to two, at which it is currently conducting research. Site selection has raised substantial public interest in most countries, and it is important that the selection process develops public confidence in a country's waste management approach. Different countries use different approaches, reflecting in part their different legal systems and different national cultures. However, the several site selection processes currently underway all seek to involve in the decision process a broad range of different stakeholders.

23. It is important to emphasize that waste disposal in any country involves a sequence of decisions spread out over decades. Each of these is, in theory, reversible although, in practice, some approaches would lend themselves to reversibility better than others. For example, switching from direct disposal of spent fuel to reprocessing would be easier if spent fuel were in long term surface storage rather than buried in a geological repository. Reasons that some stakeholders might prefer approaches that ease later reversibility include the greater ability to take advantage of new technology, of new management approaches, of enhanced safety options, of new scientific information and of changed economic circumstances.

24. The following examples summarize work on the siting and construction of repositories, and on associated research and development, in several countries that have progressed more than most.

E.3.1. United States

25. The USA is pursuing disposal of spent fuel from nuclear power plants and high level waste from the weapons programme in Yucca Mountain in the State of Nevada. The work is performed by the US Department of Energy's (DOE's) Office of Civilian Radioactive Waste Management. Scientific investigations have been ongoing at the site since 1978, although it was only approved by the President and Congress in 2002.

26. The repository design involves placing 'waste packages' of encapsulated spent fuel horizontally in tunnels (referred to as 'emplacement drifts') at a depth of about 300 m. The water table at the site is at 600 m. Over the waste packages will be drip shields to limit water contact, and in the floors of the emplacement drifts there will be additional barriers of stainless steel and crushed volcanic rock. The design allows a high degree of flexibility for adjusting such things as waste packages and package spacing. The main access to the repository will be through the original research tunnel drilled in 1997.

27. The Yucca Mountain repository is designed to be a monitored geologic repository that allows future generations the choice of either closing and sealing it as early as possible, or keeping it open and monitoring it for a longer period. The design is underpinned by a substantial science and technology programme that, among other things, takes advantage of the site's underground testing facility, which consists of tunnels, alcoves and niches where research is conducted on water flow, seepage, fractures and faults mapping, heat impact, etc.

28. Since Presidential and Congressional approval for Yucca Mountain in 2002, DOE has been preparing a formal license application for consideration by the US Nuclear Regulatory Commission. The application had earlier been scheduled for submission by the end of 2004, but has been delayed by, among other things, a court ruling in 2004 that the environmental standards set by the Environmental Protection Agency (EPA) were less stringent than required by law. New standards have now been proposed by the EPA, but they have not yet been finalized.

E.3.2. Sweden and Finland

29. Sweden and Finland are pursuing similar technology and time schedules for repository development. In both countries spent fuel will be disposed of directly without reprocessing. Although separate repositories are planned, one in each country, the design of the repositories will be similar and much of the development work is carried out as joint projects.

30. Spent fuel will be encapsulated in a copper canister with an iron insert. The iron insert provides mechanical stability and the copper shell corrosion protection. Each canister is about 4.8 m long, has a diameter of 1 m, and weighs around 25 tonnes. The canisters will be disposed of in tunnels (KBS-3H) or deposition holes (KBS-3V) at a depth of 400–700 m in crystalline bedrock. The void between the bedrock and the canisters will be filled with compacted bentonite clay (Figure 5).

31. In Sweden, the Swedish Nuclear Fuel and Waste Management Company, SKB, is currently pursuing site investigations for a deep repository in the municipalities of Oskarshamn and Östhammar, both sites close to nuclear power plants. The site investigations should be completed in 2008, and according to the current time schedule, an application to build the repository will be made at the end of 2008. Trial operation could start in 2017. During the trial operation phase 200–400 canisters will be disposed of. During and after this phase, a thorough evaluation of the repository performance will be made. The repository is expected to be filled around 2050, and the different sections of the repository can then be fully sealed.

32. In Finland, the Government made a policy decision in 2000, which was ratified by the Parliament in 2001, to proceed with a disposal project for spent nuclear fuel in Olkiluoto in the Municipality of Eurajoki and to construct an underground rock characterization facility, ONKALO, at the site. The site is close to a nuclear power plant, and the decision was supported by the Municipality of Eurajoki and by STUK, the Radiation and Nuclear Authority. Construction of ONKALO started in the summer of 2004 with the excavation of the spiral ramp tunnel. The excavation will be 420 m deep in 2008 and, eventually, 520 m deep. ONKALO is being built in a way that would also allow it to later serve as access to the repository. The application for the construction license for the disposal facility is scheduled for 2012, and the repository should be ready for use in 2020.

33. The repository development work in Sweden and Finland is already supported by an extensive research programme, including the Äspö Hard Rock Laboratory (HRL), whose activities both improve scientific understanding of important processes in the rock and test technical approaches to disposal. For example, Äspö HRL has developed a full-scale prototype of a radiation shielded and remote controlled deposition machine (Figure 6) for vertical disposal.

Figure 6. Prototype deposition machine for vertical disposal. The machine tilts the canister into the deposition hole.

E.3.3. France

34. The 1991 Bataille Law on the management of high level long lived waste committed France to a 15-year research programme focussed on three ‘axes’. Axis 1 is partitioning and transmutation. Axis 2 includes both retrievable and non-retrievable geological repositories. And Axis 3 covers conditioning and long term storage. 2006 will mark the completion of the 15-year research programme, and the Bataille law calls for a review of the research results at this stage and anticipates new Parliamentary action to adjust the French strategy based on the research results and current French priorities.

35. ANDRA, the national radioactive waste management agency, which is in charge of Axis 2, and the Commissariat à l’énergie atomique (CEA), the national research body on nuclear energy, which is in charge of Axes 1 and 3, submitted reports summarizing their research to the Government in June 2005. ANDRA’s report includes results achieved in experimental drifts at a depth of 445 m in clay. These results have been evaluated by a National Assessment Commission, composed of 12 independent scientific experts who have reviewed the full 15 years of research, by two peer reviews organized under the auspices of the OECD Nuclear Energy Agency, and by the national nuclear safety authority.

36. In addition, the French Government, in order that society as a whole should take part in the country’s forthcoming choices, submitted the subject to the National Commission on Public Debates (Commission nationale du débat public – CNDP), which organized 13 public hearings between September 2005 and January 2006.

37. A draft law based on all these inputs was put before Parliament in March 2006.

38. With respect to Axis 1, partitioning and transmutation (P&T), the research to date suggests that facilities to demonstrate P&T on an industrial scale might be possible by 2020-2025, with subsequent commercial operation possible by 2040.

39. With respect to Axis 2, retrievable and non-retrievable geological repositories, ANDRA has conducted research in a clay formation at the border of the Meuse and Haute-Marne departments in eastern France and participates in experiments in underground research laboratories (URLs) abroad, particularly in granite formations. ANDRA is considering a possible schedule for a French geological repository that would foresee construction around 2015-2020 and commercial operations starting in 2020-2025.

40. With respect to Axis 3, conditioning and long term storage, France already has substantial experience in storing vitrified HLW. Research has been designed to build on this industrial experience with storage for time horizons on the order of 50 years, with the aim of extending storage periods to 100–300 years.

41. France's future strategy will be determined by Parliament in the course of 2006. There is no requirement that Parliament choose just one of the three axes to move forward on. It may well prefer a strategy that focuses on complementarities among the three.

E.3.4. Canada, Switzerland and Japan

42. Canada, after having frozen previous generic URL research activities, has redefined its national strategy for spent fuel management. In November 2005, following a three-year nation-wide consultative process, Canada's Nuclear Waste Management Organization (NWMO) recommended an 'adaptive phased' approach to managing Canadian spent fuel. During the next 30 years spent fuel would continue to be stored at reactor sites, a suitable site for a deep geological repository would be selected, and a decision would be made whether to also construct a centralized shallow underground storage facility to start receiving spent fuel in about 30 years. With or without a centralized facility, the deep repository would begin accepting spent fuel in about 60 years.

43. In Switzerland, the revised Nuclear Energy Law adopts the concept of 'monitored geological disposal' as proposed by the Swiss Expert Group on Disposal Concepts for Radioactive Waste. It envisages a facility in which, after emplacement, waste is monitored for a substantial period before the facility is closed. The concept combines passive safety, as provided by deep disposal in a stable geological formation, with a cautious stepwise approach to implementation that is intended to address not only scientific and technical issues but also societal concerns.

44. Japan's programme on geological HLW disposal moved in 2000 from generic R&D towards implementation with the passage of the Specified Radioactive Waste Final Disposal Act and the establishment of the Nuclear Waste Management Organization of Japan (NUMO) as an implementing organization. NUMO is responsible for site selection, construction, operation, maintenance, closure and post-closure institutional control for an HLW repository. NUMO's overall schedule envisions an operating repository coming on-line in 2033–2037.

E.4. International Cooperation in Geological Disposal

45. The understanding of major processes and phenomena associated with deep geological disposal has improved significantly due in part to *in situ* observations and testing performed in underground research laboratories (URLs). URLs are expensive and limited in number. Thus international cooperation to share the opportunities and knowledge that they generate is an important complement to national research programmes and both speeds national progress and improves research cost-effectiveness.

46. The IAEA Network of Centres of Excellence promotes joint training and technical capacity building, ranging from repository design to performance assessment and site investigations, all of which also contributes, in part, to building broader confidence in geological disposal. The network makes URLs in Belgium, Canada, Switzerland, Sweden, the USA and the UK available to other countries. It helps disseminate technologies that have been developed in national and other international projects, as well as providing specific training in the areas mentioned above. As such, it complements important additional international cooperation under the auspices of the OECD/NEA, particularly in the areas of the safety case for geological disposal, waste management strategies and public involvement in decision making.

F. Multinational Options for the Storage or Disposal of Spent Fuel or Nuclear Waste

47. The management of spent fuel or radioactive waste is based on national strategies for collection, treatment, storage and disposal. According to the preamble of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management: "…radioactive waste should, as far as is compatible with the safety of the management of such material, be disposed of in the State in which it was generated". However, the preamble of the Joint Convention also notes, "…that, in certain circumstances, safe and efficient management of spent fuel and radioactive waste might be fostered through agreements among Contracting Parties to use facilities in one of them for the benefit of the other Parties". This provision recognizes that for countries that generate only limited amounts of spent fuel or waste, and for those without favourable geological sites for disposal, national facilities may prove much more expensive than in neighbouring countries with better geology and economies of scale. Developing multinational disposal options in these cases would increase the cost-effectiveness of nuclear power.

48. A number of studies have also argued that multilateral storage facilities and repositories can benefit from economies of scale and more cost-effective siting relative to the system of separate national facilities and have outlined important factors that would have to be addressed in developing multinational facilities (IAEA 2004, 2005a). These studies also highlight the need to resolve several legal and institutional issues connected to multilateral facilities and the importance of addressing political, social and public acceptance issues.

49. More recently international cooperation on the storage and disposal of spent fuel and waste has received additional attention because of its potential non-proliferation benefits. The February 2005 report of the IAEA Director General's Expert Group on Multilateral Approaches to the Nuclear Fuel Cycle reviewed the policy, legal, security, economic, institutional and technological incentives and disincentives for cooperation in various multilateral fuel cycle arrangements. The report suggested, among other things, that fuel leasing and take-back (which would require a repository accepting foreign spent fuel or HLW), the voluntary conversion of existing facilities to multinational status (including for storage and disposal), and the creation of new voluntary multinational facilities (again including storage and disposal) would all strengthen non-proliferation assurances (IAEA 2005b).

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