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Nuclear Waste: Is Everything Under Control ?

50 years after the opening of the world's first civil nuclear power station, very little radioactive waste produced has been permanently disposed of. Moreover, the average age of today's reactors is approximately 22 years, meaning most of them will be decommissioned over the next decades. All of these wastes will have to be disposed of even if no more nuclear reactors are built. But is it wise to take further advantage of the "nuclear path", without proven and widely-utilized solutions to the problem of nuclear waste?

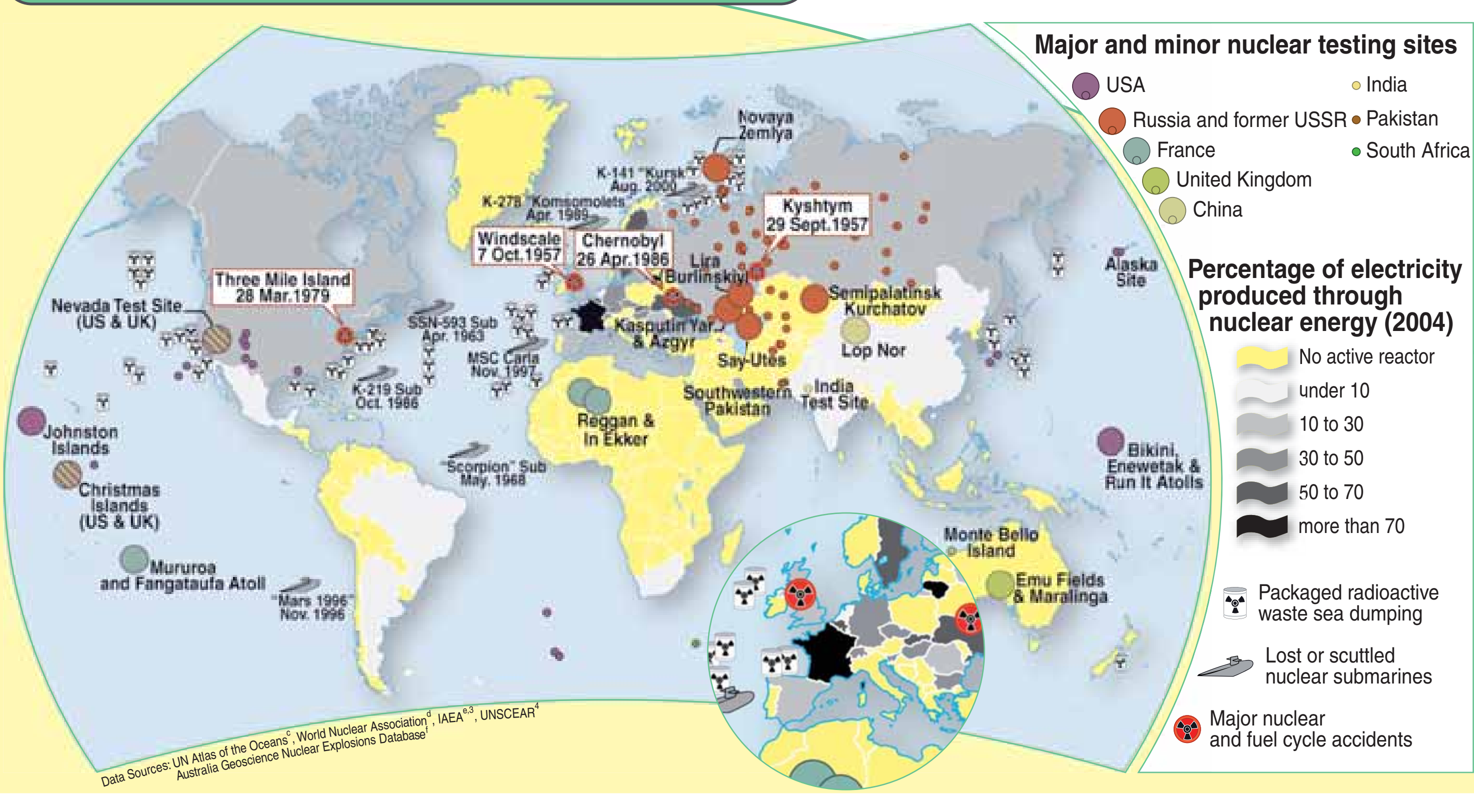
Nuclear energy supplies about 17% of the total electrical energy generated in the world[(a)]. Further expansion of nuclear power offers a tempting option given the high prices of petroleum and the pressure on countries to reduce greenhouse gases[(b)]. However, the generation of nuclear energy raises a number of concerns for the environment: **accidents** – 2006 marked the 20th anniversary of the Chernobyl accident (26 April 1986), which irradiated territories where 5.32 million inhabitants of Ukraine, Russia and Belarus live; **discharges to the environment** – especially during past, less stringent regulatory regimes; and particularly, **disposal of radioactive wastes**.

Prevention of future accidents should always be a principal safety objective of the nuclear power industry. The efforts of the international community have substantially improved nuclear safety measures over the last two decades[(1)]. Discharges of liquid and gaseous wastes to the environment are now very strictly controlled. On the other hand, the problem of radioactive waste disposal is by no means close to a solution. This is highlighted in Fig.1, which shows the extent of nuclear electricity generation, the sites of major reactor and fuel cycle accidents and the locations of past sea dumping. More strikingly, the map does not show the location of any disposal sites for civilian high-level wastes – because no such site is yet operational.

In addition to the wastes from the civilian nuclear power programme, there remains a legacy and continuing accumulation of wastes from the development of nuclear weapons. The first use of reactors involved extracting plutonium from the spent fuel for use in fission weapons. The resulting high-level wastes are still in storage and add to the wastes from civilian uses.

This bulletin concentrates on the problem of safe and environmentally acceptable disposal of the radioactive waste generated by the operation of nuclear reactors – why is the problem proving so intractable, and what needs to be done if the nuclear option is to be taken up?

Fig. 1: Nuclear concerns for the environment around the globe



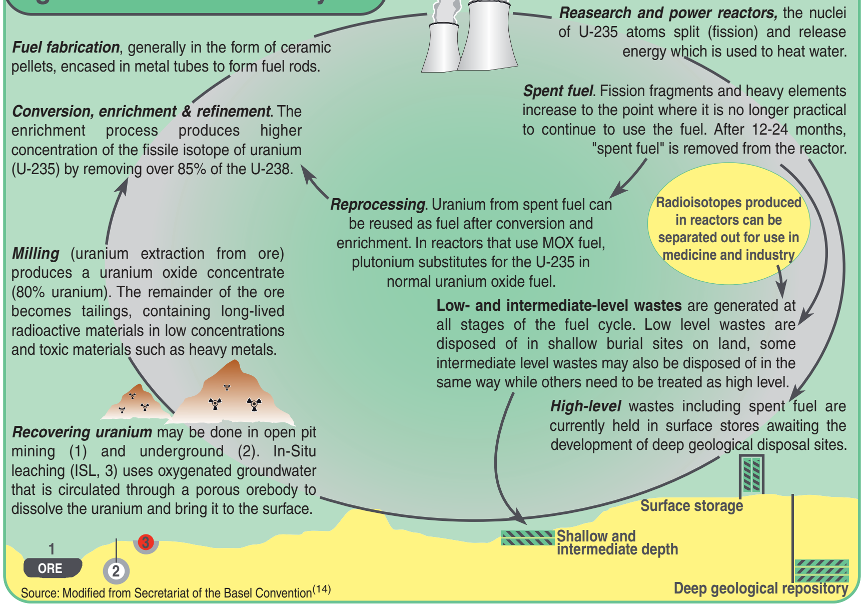
Emergence of a problem

The early development of nuclear reactors was in immediate post-war context when the primary objective was the manufacture of nuclear weapons. In this climate little attention was paid to the environmental problems that might arise. This changed significantly, in particular after the accident to a plutonium production reactor at Windscale, UK, in 1957(2). Atmospheric weapons testing led to local and global distribution of radioactive materials (fallout). This global fallout now exists as a ubiquitous addition to the natural background radiation and continues to be monitored, but nothing further can be done about it. The local situations around the weapons test sites also shown in Fig.1 have been subject to national and international examinations with recommendations for further actions in some cases. The residual wastes from the plutonium extraction process, however, still remain mainly in store.

Similarly, in the early period of development of the civilian nuclear power industry, from the 1950s to the 1970s, radioactive waste was known about but was not felt to constitute a political or social problem. The prevailing technical view was that there was no hurry to permanently dispose the wastes, and in any case that this would not be a problem. This complacent view was challenged by a number of influential studies drawing attention to the increasing quantities of wastes held in stores and the lack of an agreed disposal route. At the same time, the environmental lobby was becoming more influential and the nuclear industry suffered from problems such as high costs and accidents at Three Mile Island and Chernobyl.

Despite efforts by most countries with substantial nuclear power programmes, finding disposal routes for military and civilian high-level wastes has failed in almost all cases. The past two decades have been characterized by re-examinations of the technical options for radioactive waste management and disposal, and recognition that solving the problem is as much a social and political process as a technical one.

Fig. 3: The nuclear fuel cycle



Source: Modified from Secretariat of the Basel Convention(14)

Types of radioactive waste

It has been found useful to classify radioactive waste into three broad types. These have different levels of hazard requiring different health and safety precautions, some spontaneously generate heat from radioactive decay and thus need cooling, while some are not very radioactive and can be handled easily. These three types are known as High-level waste, Low and Intermediate-level waste and Exempt wastes. The characteristics of each type are described in Fig.2. As these are very broad categories it has sometimes been found convenient to describe particular wastes more precisely, for example, separated plutonium or Transuranic waste from military applications, but these can generally be considered as being one of the above types for most purposes, including disposal.

Where does the waste come from?

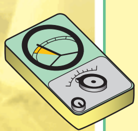
The vast majority of the waste comes from the operation of the nuclear fuel cycle which is shown in Fig. 3.

Uranium mining and milling

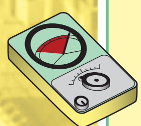
Uranium mill tailings are the radioactive sand-like materials that remain after uranium is extracted by milling. Typically around 40–50 000 tonnes of separated uranium are produced worldwide each year.

Fig. 2: Radioactive waste classifications (IAEA)

Exempt waste contains such a low concentration of activity that it does not need to be treated differently from ordinary non-radioactive waste.



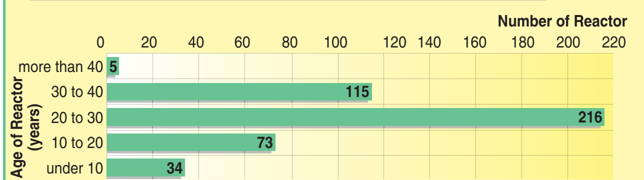
Low- and Intermediate-Level Waste (LILW) consists of items such as paper, clothing and laboratory equipment that have been used in areas where radioactive substances are handled, as well as contaminated soil and building materials. Active materials used in the treatment of gaseous and liquid effluents before they are discharged to the environment, or sludges that accumulate in the cooling ponds where spent fuel is stored are also considered LILW. Some LILW contains short-lived radionuclides or extremely low concentrations of long-lived radionuclides and is suitable for near-surface burial. LILW containing long-lived radionuclides need to be disposed of in a geological repository in a similar manner to High-Level waste.



High-level waste (HLW) is either spent fuel from a reactor, where this is regarded as a waste, or the highly active residue produced when spent fuel is reprocessed. This is initially stored as a liquid but solidified as soon as possible, for example by incorporation in borosilicate glass. High-level waste generates a considerable amount of heat and requires cooling.

Source: "Classification of Radioactive Waste" Safety Series No. 111-G-1.1 IAEA, Vienna 1994.

Fig. 4: The ageing global reactor population



This graphic presents the global number of reactors in operation by age as of 31 Dec. 2005. The majority of reactors are between 20 and 30 years old and the average age is 22. Considering that the expected lifetime of a reactor is 30 to 40 years, decommissioning is going to become a major operation over the next 50 years, leading to vastly increased quantities of radioactive wastes.

Data Source: International Atomic Energy Agency's Power Reactor Information System (IAEA's PRIS)

Electricity generation

The operation of power reactors does not give rise to very large quantities of either low- or intermediate-level radioactive wastes (LILW) during normal operation. The spent fuel is currently kept in store either at the reactor where it was produced or at a central facility.

One light-water 1 000 MW reactor produces about 100 m^3 of LILW and offloads about 30 tonnes of spent fuel each year. If this spent fuel is destined for direct disposal it comprises about 50 m^3. If it is reprocessed the amount of high-level waste is less at around 20–30 m^3 but there is an additional 50–100 m^3 of LILW produced. The installed capacity worldwide has been steady at about 350 000 MW for the past several years[6,7].

Decommissioning

As shown in Fig. 4, an increasing number of nuclear reactors are reaching the end of their life span. Typically, decommissioning of one 1 000 MW reactor is expected to generate about 10 000 m^3 of LILW, much of which will be concrete and other building material containing only small amounts of radioactivity. Nonetheless, a recent study has shown that nearly 75% of the total waste volume predicted to arise from the whole nuclear programme is from decommissioning and clearance of nuclear sites, including fuel fabrication and reprocessing sites[8].

Reprocessing

When removed from a reactor, spent fuel contains substantial useful amounts of uranium and plutonium that can be recycled as fresh fuel once the waste fission products have been removed. Most of the other radioactive materials including the fission products are retained as high-level waste. Reprocessing also gives rise to discharges to the environment and substantial quantities of both low- and intermediate-level wastes. The two main reprocessing facilities globally are La Hague (France) and Sellafield (United Kingdom). The quantity of high-level waste produced by the UK and France combined is about 200 m^3 per year.

The environmental discharges from reprocessing were high (even though within authorized limits) during the 1960s and 1970s, leading to significant concentrations of radioactive materials in the adjacent seas and seabeds (e.g. the Irish Sea bed has the highest concentrations of artificial radionuclides of any marine ecosystem). Since then the discharges have been dramatically reduced. For example, at the Sellafield reprocessing plant, total alpha and total beta discharges fell from peaks of 175 TBq (1973) and 9 500 TBq (1975) respectively to levels of 0.2 and 120 TBq in 2001[9].

Fig. 6: Radioactivity and half-lives

Activity. The rate at which a radioactive element decays and emits radiation. It is measured by the number of decays per second, measured in a unit called the becquerel. Because radioactive wastes have millions or more decays per second, the units normally used are the megabecquerel (MBq), one million decays per second, and the terabecquerel (TBq) which is one trillion decays per second. The higher the activity of the radioactive waste the more hazardous it is.

Half-life. Because radioactive elements decay they gradually become less active. The time taken for the activity to fall to half its starting value is called the half-life. Radionuclides with short half-lives decay away rapidly and are not a problem in waste management (e.g. radioiodine has a half-life of 8 days so after a few months there is essentially none left); conversely radionuclides with long half-lives present a concern even over geological timescales (e.g. plutonium has a half-life of 24 000 years).

Military wastes

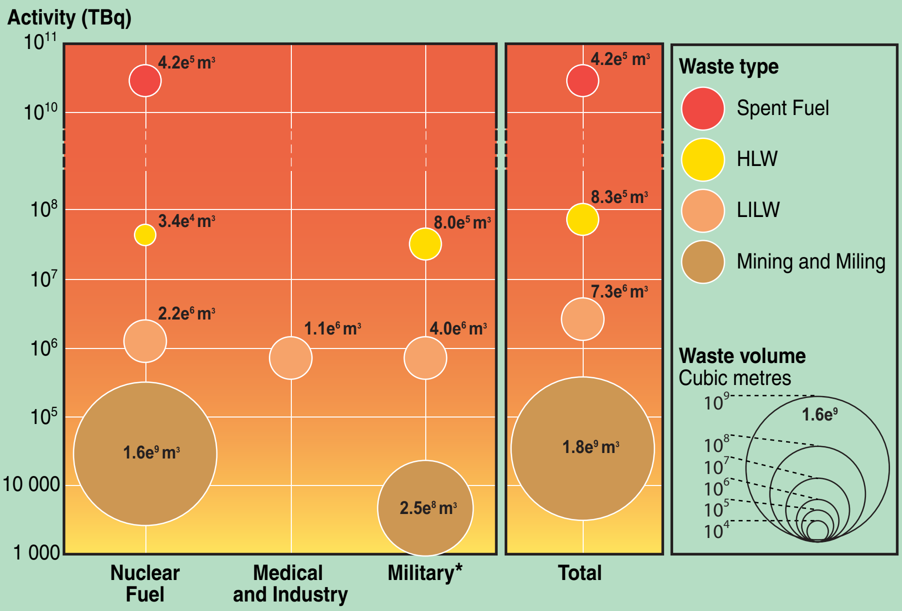
The manufacture and maintenance of nuclear weapons produces a particular type of waste known as Transuranic (TRU) waste. The most prominent radionuclide in most TRU waste is plutonium. Following declassification of certain military information, revelations of extensive dumping of military wastes and reactors in the Russian Arctic, and of other examples of careless past disposal, added a new dimension to the problem.

Further quantities of wastes are generated by the dismantling of old weapons, including 50 tonnes of plutonium in the USA for example[10]. The global plutonium stockpile is estimated at 1 100 tonnes and growing rapidly[11]. Even though some of this plutonium can be recycled in reactors as a fuel, the disposal of the growing amounts of separated plutonium and of TRU must in particular be carefully planned to meet both environmental and non-proliferation objectives.

Medical and Industrial applications

Radioactive sources are very widely used in hospitals (e.g. diagnostic radiology and radiotherapy) and industrial facilities (e.g. for sterilization and industrial radiography). Many accidents have occurred involving waste sources, of which one of the worst was at Goiania[12] in Brazil in 1987, showing that despite their relatively small total quantity and activity, these represent one of the most potentially hazardous forms of waste.

Fig. 5: Cumulative global radioactive waste inventories



This graphic represents the cumulative global radioactive waste inventory as compiled by the International Atomic Energy Agency up to the year 2000. Different types of activities generate variable amounts of nuclear waste with respective activity. Spent fuel represents the smallest amount of waste generated in total, but holds the highest activity. The largest amounts of wastes are generated by mining and milling, but contain an activity only a millionth of that in spent fuel.

*Estimates are highly uncertain. In some countries there is no clear separation between reprocessing for military and for civilian purposes.
Data source: IAEA

Fig. 7: Southern Ural nuclear facilities

A violent explosion on 29th September 1957 in the Chelyabinsk-40 complex in Kyshtym, southern Urals, involving dry nitrate and acetate salts in high level waste storage tanks, spread radioactivity over a large area later called the "Kyshtym footprint". The total amount of activity released was of the order of 500 000 TBq of fission products. The area contaminated was nearly 20 000 km^2, of which 1 000 km^2 was above the permissible limit. At the time, over 270 000 people lived in this highly contaminated zone, of whom 10 000 were eventually evacuated. The accident was concealed at the time and only came to light in the 1980s.

Nuclear power station (NPS)

Nuclear industry and research site (civil and military). Fuel production or recycling.

Nuclear weapons test site. Large areas contaminated with radioactive fallout

Area known as the "Kyshtym footprint" or "East Urals Radioactive Trace" (EURT).

Russian region specialized in civil and military nuclear industries. Former relationship with Central Asian nuclear facilities.

Source: Modified from original map appearing in UNEP 2005[15]. Original maps by Philippe Rekacewicz, UNEP/GRID-Arendal.

What can be done with the wastes?

Storage

Nearly all wastes will be placed in a facility for some time, with the ability to retrieve them. Thus storage is an essential step in radioactive waste management, although the duration of storage varies.

For low- and intermediate-level wastes, if they have only very short-lived radioactive components, it is worthwhile to store them to allow the radioactivity to decay away - this makes management easier; otherwise there is no real technical or safety gain in prolonging the storage time.

High-level wastes have the problem of heat generation in addition to their radioactivity. This reduces significantly with storage over a few decades. For this reason, most high-level waste management strategies have deliberately incorporated a period of storage up to about 50–100 years as the optimum procedure. Some environmental groups have advocated longer-term storage to enable further research and to leave options open for future generations. However, the safety of storage relies on active institutional controls and continued expenditure, so this could also be regarded as passing the problem and the costs on to future generations. Indeed, one of the most serious accidents to date at Kyshtym involved a high-level liquid waste storage tank (Fig.7). It is also relevant that, when viewed in terms of a geological time frame, human institutions and agreed plans are not necessarily reliable. Taking these matters into account, there seems now a general consensus building that it would be best to proceed to disposal after a period of storage that allows for thermal decay.

Disposal

The scientific community cannot be accused of thinking narrowly when it comes to the problem of disposing of radioactive waste. Transmutation, disposal into space or by melting through the Arctic ice have all been proposed. However, the range of practicable options can be divided into those at sea and those on land.

Sea disposal

In the early days, low- and intermediate-level wastes were dumped at a number of sites (Fig.1) under the guidelines and definitions adopted by the 1972 London Convention[i]. However, the opposition to this disposal route gradually intensified and is now effectively banned. Considerable research was carried out during the 1970s and 1980s into the possibility of disposing of high-level waste on or under the seabed. However, it was vehemently opposed by all environmental groups and many governments, and is no longer regarded as politically credible.

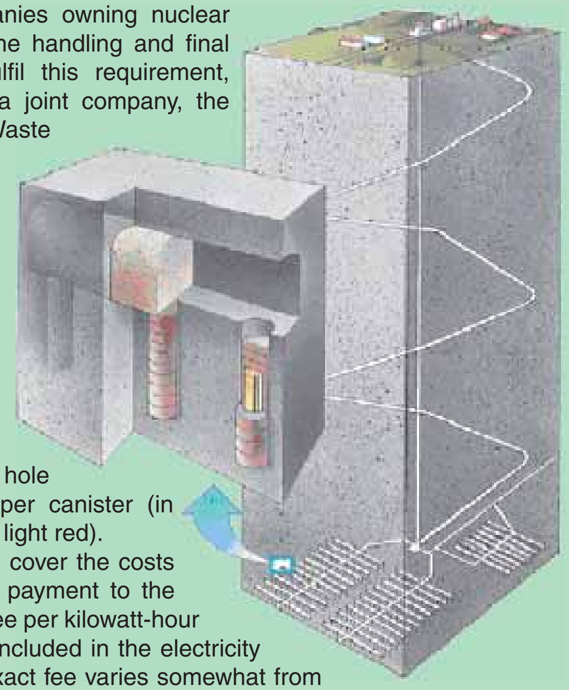
Land disposal

Since the start, low-level wastes have been disposed of by shallow burial. Many early disposal sites consisted of no more than a trench scooped out of the earth. Over the last few decades, better engineered facilities have been used, with the trenches lined and wastes appropriately packaged. For the large quantities of low-level wastes there is no alternative to continuing with this practice, using up-to-date procedures to ensure the safety of the facilities. All countries with a nuclear power industry operate low-level waste shallow burial facilities. The sites can be monitored so that remedial measures can be taken if necessary; which will almost certainly be needed for some past sites.

Details of proposed geological repository designs for high-level wastes vary between countries but all of them envisage a repository at a depth of at least several hundred metres in a suitable stable rock formation with the wastes being fully conditioned before disposal (see Figure 10). There is still debate over how long the wastes should be maintained in a "retrievable" state but at some point while the repository is still under institutional control it will be closed. After this the safety of the repository relies on a combination of barriers to prevent the radioactive materials reaching the biosphere. Some of these are engineered such as the incorporation of reprocessing wastes in borosilicate glass with very slow leaching properties, the use of durable materials as waste canisters and the use of absorbent back-fill materials. However in the long term the principal reliance is on the stability and size of the rock mass itself. Given the extremely long timescales, a mathematical demonstration of safety becomes increasingly unreliable. Attention has now switched to more robust and "common-sense" analogues to meet the safety goal "to protect human health and the environment now and in the future, without imposing undue burdens on future generations"(13).

Despite the general consensus that disposal is the preferred option, nearly every country which has attempted to find a safe burial site for high-level waste has so far failed, primarily because of political opposition, even if technical reasons are sometimes an issue for certain sites: countries have been facing both more geological complexities and political opposition than expected. A few countries have made some progress. In Finland, there has been a start on construction of a repository at Olkiluoto, and in Sweden there is a detailed repository design and some communities have expressed their willingness to host a site. The Nuclear Waste Management organisation in Canada has recommended geological disposal and both France and Germany are moving in the same direction. Germany has a deep geological facility at Konrad that has been licensed but is not yet operational. In the United States, there is an operating geological repository in New Mexico (The Waste Isolation Pilot Plant) for military-origin wastes, and a proposed civilian facility at Yucca Mountain. However, there is still a very long way to go before any significant proportion of the current high-level waste accumulation is permanently disposed of.

Fig. 8: A typical design of a geological repository for high-level waste The Swedish example



Swedish law requires that companies owning nuclear power plants be responsible for the handling and final disposal of nuclear waste. To fulfil this requirement, nuclear companies have formed a joint company, the Swedish Nuclear Fuel and Waste Management Co. (SKB).

The industry conducts research for final disposal and supervises existing waste facilities that are in operation. The Swedish KBS-3 is designed for spent fuel repository in which vertical waste deposition holes extend downwards (500 metres deep) from larger horizontal tunnels, which would eventually be backfilled. The illustration shows each deposition in eight metre deep hole containing a two metre high copper canister (in yellow) surrounded by bentonite (in light red).

The financing system created to cover the costs of nuclear waste is based on the payment to the state by the reactor licensees of a fee per kilowatt-hour of electricity produced. The fee is included in the electricity price paid by the consumer. The exact fee varies somewhat from year-to- year. The fee is calculated by SKB and established by the Government and then paid into the state Nuclear Waste Fund which administers the funds, based on the assumption that the facilities will be operative for 25 years.

Source: Swedish Nuclear Fuel and Waste Management Co. at www.skb.se

Finding solutions

Stakeholder involvement

Over the last decade there has been a shift of emphasis from the technological to the social aspects of trying to reach political and public consensus of waste disposal strategies and for actual disposal sites. Countries such as France, Canada and the UK together with international groups especially the Nuclear Energy Agency of OECD and the European Commission have carried out broad-ranging reviews and research to try to understand the reasons behind past failures to obtain agreement on proposals. One common outcome of these reviews has been a recognition that it is essential to involve stakeholders in the deliberative process. One of the conclusions of the UK study(8) was that the analysis of international experience has shown that "the past practice of deciding where repositories should be built without an extensive engagement with the local community has always failed". It will be necessary for all governments and waste management authorities to take this message on board and work though a genuine dialogue towards creating a climate of mutual understanding and trust.

Financing

A different but very important concern is over the financing of waste management and disposal. This remains one of the imponderables that will need to be settled, or at least made less uncertain, before there is commercial, rather than governmental commitment to new nuclear power programmes. To do so needs not only a firmer grasp of the engineering works and the timescales over which it is to be carried out, but also the financing mechanisms. In this respect the Swedish example shown in Fig.8 may be an interesting precedent.

International conventions and relevant international bodies

At the 1992 Rio Conference of the United Nations on Environment and Development, 179 Governments voted to adopt the programme of Agenda 21. One of the programme areas was the safe and environmentally sound management of radioactive wastes. This encourages states to support efforts within the International Atomic Energy Agency to develop and promulgate waste safety standards, to strengthen efforts to implement the Code of Practice on the Transboundary Movement of Radioactive Waste and to encourage the London Dumping Convention to expedite work leading to a moratorium.

The Parties of the 1972 London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter agreed in 1993 to ban the dumping of all radioactive wastes. This legally binding prohibition entered into force on 20 February 1994.

In 1997, The Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management was adopted by a diplomatic conference of the IAEA. Entering into force on 18 June 2001, it is the first international agreement on the safety of spent fuel and the management of radioactive waste, and to a substantial extent codifies the requirements of the Code of Practice mentioned above.

The IAEA, based in Vienna, Austria, was founded in 1957. It develops safety standards, guidelines and recommendations, and provides technical guidance to member states regarding radiological practices and protection which now include a complete suite of standards relating to waste safety including safe disposal. The basis for radiological protection in the IAEA standards is provided by UNSCEAR (see below), and by the International Commission on Radiological Protection (ICRP), which has issued specific recommendations on radioactive waste management since 1985.

The activities of the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA), based in Paris, France, complement those of the IAEA. It has a variety of waste management programs involving its 27 member states, and works closely with the IAEA on nuclear safety standards and other technical activities. It has been particularly active in promoting the concept of stakeholder involvement.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), established by the General Assembly of the United Nations in 1955, independently assesses and reports levels and effects of exposure to ionizing radiation. Governments and organizations throughout the world rely on the Committee's estimates as the scientific basis for evaluating radiation risk, establishing radiation protection and safety standards, and regulating radiation sources. The UNSCEAR Secretariat has been functionally linked with UNEP since 1974.

Conclusion

The development of nuclear weapons and later of nuclear power has, over the past several decades, resulted in a substantial accumulation of radioactive waste currently in storage. Whether or not there is any further construction of power stations, the existing waste and that resulting from decommissioning will have to be safely disposed of. There is currently no operational disposal route for much of this waste, especially the high-level waste that contains 93% of the total radioactivity. It is increasingly likely, given the ever-growing demand for energy and the diminution of economically extractable fossil fuels and their own environmental consequences, that many countries' energy needs will not be met by alternative sources and energy conservation alone, and thus that some countries will consider pressing ahead with the nuclear option. Before considering this option, however, countries should take the political and technical steps necessary to begin the process of disposing of their accumulated waste stockpiles to ensure that viable and proven disposal routes exist for all new wastes that will be generated.

Unrehabiliated uranium tailings in Tajikistan (Photo: F. Harris/IAEA)

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