NUCLEAR POWER:
MYTH AND REALITY

NO. 3 | FEB 2006 | ENGLISH VERSION

Nuclear Fuel Cycle

Nuclear Issues Paper No. 3

BY JÜRGEN KREUSCH, WOLFGANG NEUMANN, DETLEF APPEL (Chapters 1 and 3), and PETER DIEHL (Chapter 2)

Contents

HEINRICH
BÖLL
STIFTUNG

The Authors

Detlef Appel studied geology in Hanover and Vienna. He worked in a research capacity from 1971 to 1981 at the University of Hanover, where he received his doctorate in 1979. Since 1981, he has been an independent consultant and inspector in the "environmental geosciences" sector. He specialises in overall strategies and individual solutions for ground water and soil conservation, environmental impact analyses, dumps, abandoned polluted areas, and final storage sites for radioactive waste.

Peter Diehl has been involved in uranium mining issues since 1982, when he joined a local environmental group opposing development of a new uranium mine in the Southwestern part of Germany. In the late 1980s and early 1990s he was busy networking among environmental groups concerned about uranium mining all over Europe. Since 1995, he is running the Uranium Project of the World Information Service on Energy (WISE), an Amsterdam-based NGO providing networking services for anti-nuclear groups worldwide.

Jürgen Kreusch was born in 1952. He studied geology in Marburg and Hanover, specializing in geophysics, geological engineering, and hydrogeology. He has done inspection and consulting work at the Gruppe Ökologie e.V. since 1980, focusing on disposal of radioactive and toxic chemical waste. Since 1988, he has also been a co-managing director of intac GmbH, a company that provides consulting, strategic and inspection services on technology and the environment.

Wolfgang Neumann is a physicist. He works on nuclear issues for the Gruppe Ökologie of the Institut für ökologische Forschung und Bildung e.V. in Hanover. As an inspector and appraiser, Wolfgang Neumann advises citizens' groups, environmental associations, members of Parliament, agencies and administrations at the federal, state and municipal levels. He has produced a large number of studies and evaluations in this capacity. Since 1999 he has been a member of the "Supply and Disposal" committee of the Reactor Security Commission (RSK) and the "Plant Radiation Protection" committee of the Radiation Protection Commission (SSK) at the Federal Ministry of Environmental Affairs, Conservation and Reactor Safety. Before these appointments, he was a member of the "Radiation Commission" of the Bund für Umwelt und Naturschutz Deutschland e.V.

Nuclear Issues Papers, No. 3:
Nuclear Fuel Cycle
By Jürgen Kreusch, Wolfgang Neumann, Detlef Appel, and Peter Diehl

Co-published by wise

A publication of the Heinrich Böll Foundation Regional Office for Southern Africa, in co-operation with the Heinrich Böll Foundation headquarter.

Contact:
Heinrich Böll Foundation Regional Office for Southern Africa, PO Box 2472; Saxonwold, 2132; South Africa. Phone: +27-11-447 8500. Fax: +27-11-447 4418. info@boell.org.za
Heinrich Böll Foundation, Rosenthaler Str. 40/41, 10178 Berlin, Germany.
Tel.: ++49 30 285 340; Fax: ++49 30 285 34 109; info@boell.de; www.boell.de/nuclear

1 The Nuclear Fuel Cycle

The use of nuclear energy involves the work of several very different industrial plants. Each of these plant types has a specific hazardous potential. It starts with the dust in uranium mines, continues with potential and actual radioactive burdens in cases of normal operation, accidents for workers in the nuclear facilities or people living nearby, and ends with the possible contamination of groundwater in a final repository for radioactive waste.

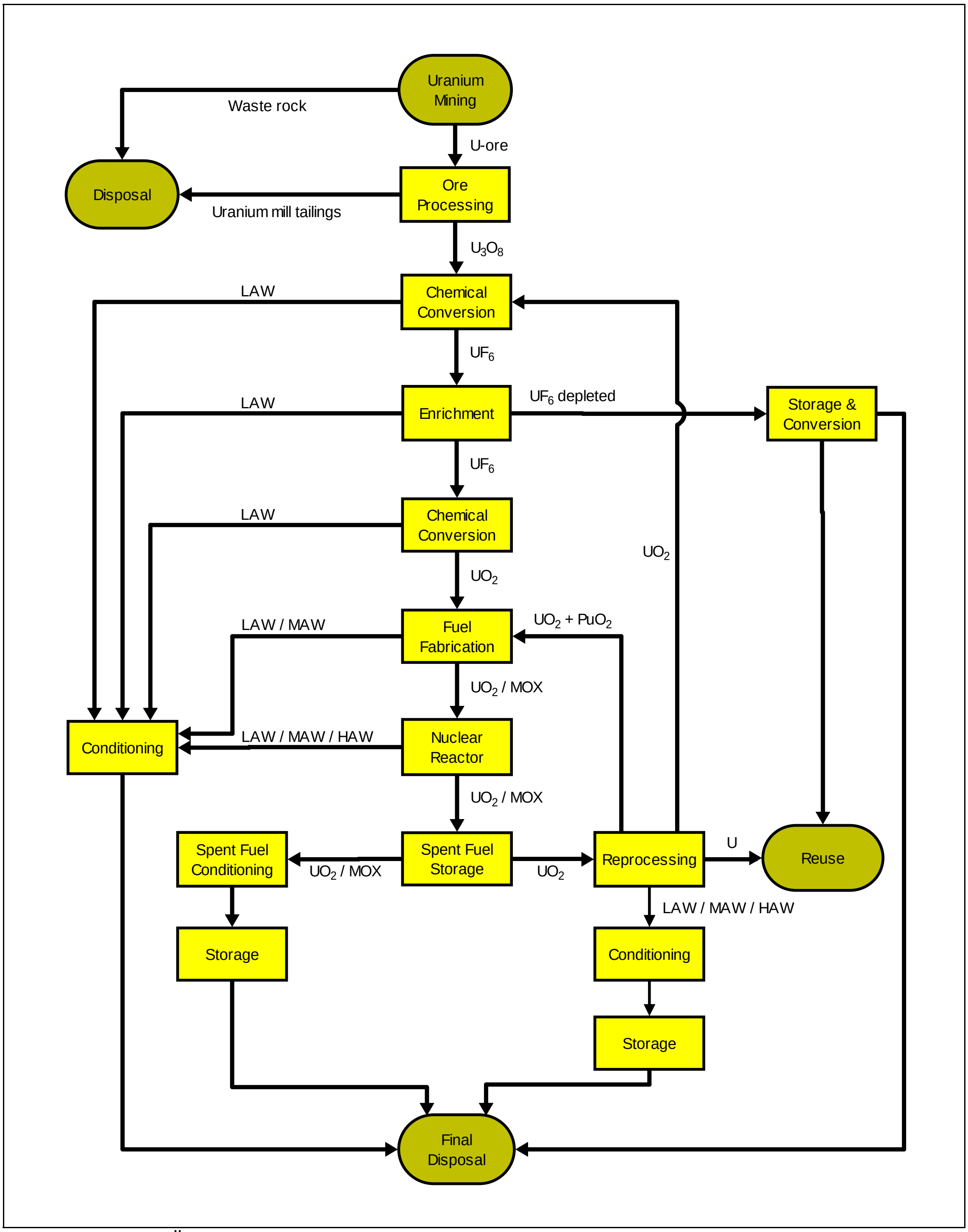
The necessary steps for uranium to become a fuel element are shown in the following illustration (Fig. 1). After the use of uranium fuel in the nuclear power plant and the necessary storage time, there are two possible ways to handle the spent fuel. The first one is conditioning and “direct” final disposal and the second one is reprocessing. Reprocessing means the separation of uranium and the produced plutonium from the spent fuel, fabrication of new fuel elements with this material, and reuse in a reactor. Most countries using nuclear energy do not reprocess their spent fuel. More detailed information for reprocessing is given in a later chapter.

The enrichment results in a large amount of depleted uranium (tails). Every enrichment facility produces several thousand megagrams of this material in a year. Because of economic reasons, it is not certain what will be done with this radioactive material in the future. It might be that only a small part can be used outside the nuclear fuel cycle and the rest has to be disposed of completely.

Radioactive waste is produced in every nuclear facility. The waste can be categorized as low-active (LAW), medium-active (MAW) and high-active (HAW). Compared with the other two categories, HAW represents a small amount in volume but it concentrates some orders of magnitudes of the activity. The main parts of HAW are the spent fuel for “direct” final disposal, the vitrified fission products from reprocessing and, in a reactor, activated materials. LAW and MAW are generated on a larger spectrum. The quantity of the waste depends on the reactor type and the requirements for the waste management, including final disposal; these factors differ depending on the country. For example a 1,300 MWe pressure-water reactor in Germany produces about 60 m^3 LAW and MAW as well as about 26 Mg of spent fuel every year. Through to decommissioning, this reactor produces 5,700 m^3 LAW. For the use of nuclear energy, considering the operational limitation of 35 years per reactor, about 300,000 m^3 of total waste for final disposal is predicted for Germany.

With or without reprocessing, a repository for the final disposal of radioactive waste is necessary. That is true not only for the large amount of LAW and MAW but also for spent fuel, because up until now, mixed-oxide spent fuel has not been reprocessed on an industrial scale. Only in France is it done on a small scale. No repository for HAW and spent fuel is available anywhere in the world. Repositories for LAW and MAW are in operation in some countries with large nuclear programs. It is absolutely necessary that a final disposal repository be built as quickly and as safely as possible for all countries using nuclear energy. Final disposal should offer more safety than other options if the disposal site is careful chosen and constructed. The negative burdens of nuclear energy must be managed.

Fig. 1. Idealized representation of fuel cycle with and without reprocessing as it could be realized



Source: Gruppe Ökologie

2 Uranium Mining

Introduction

The era of uranium mining on a large scale began after the end of World War II, when uranium was mined as a strategic resource. Great efforts were undertaken to get at this raw material for the nuclear bomb at any cost, initially ignoring impacts on workers' health and the environment. The United States obtained their uranium from a variety of sources, mainly from domestic and Canadian deposits. The Soviet Union, initially not aware of any larger domestic deposits, established a huge uranium mining industry in its European satellite states, in particular East Germany and Czechoslovakia, but also in Hungary and Bulgaria, among others. At times, more than 100,000 people struggled under harsh conditions at the East German "Wismut" operation to supply the same amount of uranium that nowadays is produced by a few hundred people from a Canadian high-grade deposit.

With uranium more and more becoming a commercial resource for nuclear power generation in the 1970s, the situation began to change: a market for uranium developed—since governments were no longer the sole customers for the uranium—and environmental standards for uranium mining were enforced. With the end of the Cold War, military demand for uranium ceased, and secondary resources such as stock holdings or downblended nuclear bomb material became available. These secondary resources are currently supplying nearly half of the demand of the nuclear power industry, and they are leaving the chance of survival only to the most economical mines. With the foreseeable end of the availability of secondary resources, and proposals for the expansion of nuclear power generation being made in several countries, the situation is changing again: uranium might once again become a scarce resource that has to be mined at high (environmental) cost.

Uranium mining: technology and impacts

At an average concentration of 3 g/t in the earth's crust, uranium is not a particularly rare metal. Extraction, however, makes sense only in deposits containing concentrations of typically 1000 g/t (0.1%) at least; lower grades are currently being mined in very special circumstances only. Mineable concentrations have accumulated in many deposits in various parts of the world. These deposits show wide variations in geologic setting, size, uranium grade, and accessibility to mining. On the Colorado Plateau in the western United States where the typical ore grade is 0.1–0.2 percent, uranium was mined in thousands of mostly small mines up to the early 1980s, when the uranium price collapsed. In Elliot Lake (Ontario, Canada), East Germany, and Czechoslovakia, for example, uranium was mined for decades mostly in very large underground mines and often at even lower ore grades. When the East German uranium mining operations were halted in 1990, their mining cost was approximately ten times the world market price.

After the end of the Cold War, only the most economical uranium mining operations could continue. The highest grade currently being mined (an extraordinary 17.96 percent) is that of the McArthur River underground mine in Saskatchewan, Canada, while the lowest grade currently being mined on a large scale (0.029 percent) is that at the Rössing open-pit mine in Namibia.

Most uranium is mined conventionally—in open-pit or underground mines. Except for a few high-grade deposits in Saskatchewan, Canada, ore grades are below 0.5 percent, and large amounts of ore have to be mined to get at the uranium. In the mines, workers are exposed to dust and radioactive radon gas, presenting a lung cancer hazard. During the early years of uranium mining after World War II, mines were poorly ventilated, leading to extraordinarily high concentrations of dust and radon in the mine air. In 1955, typical radon concentrations in Wismut's mines were approximately 100,000 Bq/m^3, with peaks of 1.5 million Bq/m^3. A total of 7,163 East German uranium miners died from lung cancer between 1946 and 1990. For 5,237 of them, the occupational exposure was acknowledged as the cause of the disease. In the United States, Congress recognized the government's responsibility for the health of the early uranium miners (mostly Navajo) only in 1990 by passing the Radiation Exposure Compensation Act. The administrative hurdles for obtaining compensation were so high, and the funds allocated for this program were so insufficient, that many miners (or surviving family members) received compensation only after the law was amended in 2000.

During mining operation, large volumes of contaminated water are pumped out of the mine and released to rivers and lakes, spreading into the environment. Effluents from the Rabbit Lake mine in Saskatchewan, Canada, for example, are causing a sharp increase in uranium loads in the sediment of Wollaston Lake's Hidden Bay. While natural uranium levels in the lake sediment are below 3 µg/g, levels in Hidden Bay had reached approximately 25 µg/g in 2000, and have more than doubled each year since then, reaching 250 µg/g in 2003. In river sediments of Wismut's Ronneburg mine area, concentrations of radium and uranium around 3000 Bq/kg were found, indicating up to 100-fold increases over natural background.
Ventilation of the mines, while lowering the health hazard for the miners, releases radioactive dust and radon gas, increasing the lung cancer risk of residents living nearby. At Wismut's former Schlema-Alberoda mine, for example, a total of 7426 million m^3 (235 m^3/s) of contaminated air was blown into the open air in 1993, with average radon concentrations of 96,000 Bq/m^3.

Waste rock is produced during open-pit mining when removing overburden, and during underground mining when driving tunnels through non-ore zones. Piles of so-called waste rock often contain elevated concentrations of radionuclides when compared to normal rock. Other waste piles consist of ore with too low a grade for processing. All these piles continue to threaten people and the environment after shutdown of the mine due to their release of radon gas and seepage water containing radioactive and toxic materials. The waste rock piles of Wismut's uranium mines in the Schlema/Aue area contain a volume of 47 million m^3 and cover an area of 343 hectares. The waste rock often was dumped on the valley's slopes in the immediate neighborhood of residential areas. Consequently, high radon concentrations in the free air of around 100 Bq/m^3 were found in large areas of Schlema before the waste rock was covered, and in some quarters the level was even above 300 Bq/m^3. The independent Ecology Institute had calculated a lifetime excess lung cancer risk of 20 cases (and 60 cases respectively) per 1,000 inhabitants from these concentrations. In addition, waste rock was often processed into gravel or cement and used for road and railroad construction. Thus, gravel containing elevated levels of radioactivity was dispersed over large areas.

In some cases, uranium is recovered from low-grade ore by **heap leaching**. This is done if the uranium contents is too low for the ore to be economically processed in a uranium mill. The alkaline or acidic leaching liquid (often sulfuric acid) is introduced on top of the pile and percolates down until it reaches a liner below the pile, where it is caught and pumped to a processing plant. In Europe, this technique had been in use until 1990 in East Germany and in Hungary, for example.
During leaching, such piles present a hazard because of the release of dust, radon gas, and leaching liquid. After completion of the leaching process, a long-term problem may result from naturally induced leaching if the ore contains the mineral pyrite (FeS_2), as is the case with the uranium deposits in Thuringia, Germany, and Ontario, Canada. Then, the access of water and air may cause a continuous, bacterially-induced production of sulfuric acid inside the pile, which results in the leaching of uranium and other contaminants for centuries and possibly the permanent contamination of groundwater. While heap leaching became less important during the depression of uranium prices, it may experience a revival if the mining of low-grade ores becomes of interest again.

An alternative to conventional mining is **solution mining**. This technology, also known as “in-situ leaching,” involves injection of an alkaline or acidic leaching liquid (e.g., ammonium-carbonate, or sulfuric acid) through drill-holes into an underground uranium deposit, and the pumping of the uranium-bearing liquid back to the surface. Thus, other than conventional mining, this technology does not require removal of the ore from the deposit. This technology can only be used for uranium deposits located in an aquifer in permeable rock, not too deep (approx. 200m) in the ground, and confined in non-permeable rock.
The advantages of this technology are the reduced risks for the employees from accidents and radiation, the lower cost, and no need for large tailings piles. Major disadvantages are the risk of leaching liquid excursions beyond the uranium deposit and subsequent contamination of groundwater, and the impossibility of restoring natural conditions in the leaching zone after finishing the leaching operation. The contaminated slurries arising are either dumped in some surface impoundments, or injected into so-called deep disposal wells.
Historically, in-situ leaching was used on a large scale, involving the injection of millions of tonnes of sulfuric acid, at Stráz pod Ralskem, Czech Republic, various sites in Bulgaria, and, in a slightly different scheme, in Königstein, East Germany. In the case of Königstein, a total of 100,000 tonnes of sulfuric acid was injected with the leaching liquid into the ore deposit. After the shutdown of the mine, 1.9 million m^3 of leaching liquid were still locked in the pores of the rock leached so far; a further 0.85 million m^3 were circulating between the leaching zone and the recovery plant. The liquid contains high contaminant concentrations, for example, expressed as multiples of the drinking water standards: cadmium (400x), arsenic (280x), nickel (130x), uranium (83x), etc. This liquid presents a hazard to an aquifer that is important for the drinking water supply of the region. Groundwater impact is much larger at the Czech in-situ leaching site of Stráz pod Ralskem, where 3.7 million tonnes of sulfuric acid were injected: 28.7 million m^3 of contaminated liquid is contained in the leaching zone, covering an area of 5.74 km^2. Moreover, the contaminated liquid has spread out beyond

the leaching zone horizontally and vertically, thus contaminating another area of 28 km^2 and a further 235 million m^3 of groundwater.
With the decrease of uranium prices during the last decades, in-situ leaching became the only source of domestic uranium in the United States. Meanwhile, in-situ leaching is gaining importance worldwide for the exploitation of low-grade deposits, and new projects are in development in Australia, Russia, Kazakhstan, and China.

Ore mined conventionally in open-pit or underground mines is first crushed and leached in a **uranium mill**. The mill is usually located near the mines to reduce transport. The uranium is then extracted in a hydrometallurgical process. In most cases, sulfuric acid is used as the leaching agent, but alkaline leaching is also used. As the leaching agent not only extracts uranium from the ore, but also several other constituents like molybdenum, vanadium, selenium, iron, lead, and arsenic, the uranium must be separated from the leaching solution. The final product produced from the mill, commonly referred to as "yellow cake" (U_3O_8 with impurities), is packed and shipped in casks. The major hazard resulting from the milling process is from dust emissions. When closing down a uranium mill, large amounts of radioactively contaminated scrap have to be disposed of in a safe manner.

The residue from the milling process, the **uranium mill tailings**, have the form of a slurry. They are usually pumped to settling ponds for final disposal. The amount of tailings produced is virtually identical to that of the ore mined, since the uranium extracted represents only a minor fraction of the total mass. The amount of tailings generated per tonne (t) uranium extracted thus is inversely proportional to the ore grade (the uranium concentration in the ore).
The largest uranium mill tailings dam worldwide probably is that of the Rössing uranium mine in Namibia; it contains more than 350 million t. The largest such tailings piles in the United States and Canada contain up to 30 million t of solid material. In eastern Germany, the largest pile contains 86 million t.
In the early years, however, tailings were in some cases simply released into the environment without any control. The most disturbing example is the case of Mounana, Gabon, where this practice was continued until 1975: a subsidiary of the French company Cogéma mined uranium there from 1961. During the first fifteen years of operation, the uranium mill tailings were released into the next creek. A total of 2 million t of uranium mill tailings thus were dispersed in the environment, contaminating the water and forming deposits downstream in the river valley. When mining ceased in 1999, the dispersed tailings were just covered with a thin erosion-prone layer of neutral soil, rather than clearing them away and disposing of them.

Apart from the portion of the uranium removed, the tailings slurry contains all the constituents of the ore. As long-life decay products of the uranium, such as thorium-230 and radium-226, are not removed, the slurry still contains 85 percent of the initial radioactivity of the ore. Due to technical limitations, all of the uranium present in the ore cannot be extracted. Therefore, the slurry also contains some residual uranium. In addition, the slurry contains heavy metals and other contaminants such as arsenic, as well as chemical reagents added during the milling process.

Radionuclides contained in uranium tailings typically emit 20 to 100 times as much gamma-radiation as natural background levels on deposit surfaces. The gamma radiation hazard is rather localized, though, since levels decrease rapidly with distance from the pile.
When the surface of the pile dries out, fine sands are blown by the wind over adjacent areas. The sky was darkened from storms blowing up radioactive dust over villages located in the immediate vicinity of East German uranium mill tailings piles, before they were protected with covers. Subsequently, elevated levels of radium-226 and arsenic were found in dust samples from these villages.
The radium-226 in tailings continuously decays to the radioactive gas radon-222, the decay products of which can cause lung cancer when inhaled. Some of this radon escapes from the interior of the pile. The radon release rate is rather independent from the ore grade; it depends mainly on the total amount of uranium initially contained in the ore processed. Radon releases are a major hazard that continue after uranium mines are shut down. The US Environmental Protection Agency (EPA) estimated the lifetime excess lung cancer risk of residents living nearby a bare tailings pile of 80 hectares at two cases per hundred.
Since radon spreads quickly with the wind, many people receive small additional radiation doses. Although the excess risk for the individual is small, it cannot be neglected due to the large number of people concerned. Assuming a linear no-threshold dose effect, the EPA estimated that the uranium tailings deposits existing in the United States in 1983 would cause 500 lung cancer deaths per century, if no countermeasures were taken.

Seepage from tailings piles is another major hazard. Seepage poses a risk of contamination to ground and surface water. Residents are also threatened by uranium and other hazardous substances, like arsenic, in their drinking water supplies and in fish from the area. The seepage problem is very important with acidic tailings, as the radionuclides involved are more mobile under acidic conditions. In tailings containing pyrite, acidic conditions automatically develop due to the inherent production of sulfuric acid, which increases migration of contaminants to the environment. Total seepage from Wismut’s Helmsdorf tailings deposit before reclamation was estimated at 600,000 m^3 per year; only about half of this amount was intercepted and temporarily pumped back to the deposit, until a water treatment plant became operational. This seepage had a high contaminant load, expressed as multiples of drinking water standards, for example: sulfate (24x), arsenic (253x), uranium (46x). At the Hungarian uranium mill tailings deposit of Pécs, contaminated groundwater migrates at a speed of 30 to 50 m per year toward the drinking water wells of the city.
Due to the long half-lives of the radioactive constituents involved, safety of the tailings deposits has to be maintained for very long periods of time, but the deposits are subject to many kinds of erosion. After rainfall, erosion gullies can form; plants and burrowing animals can penetrate into the deposit and thus disperse the material, enhance the radon emanation, and make the deposit more susceptible to climatic erosion. In case of earthquakes, strong rain, or floods, tailings deposits can even fail completely. Such failures have occurred in 1977 in Grants, New Mexico, United States, leading to the spill of 50,000 t of slurry and several million liters of contaminated water, and in 1979 in Church Rock, New Mexico, leading to the spill of more than 1000 t of slurry and about 400 million liters of contaminated water, for example.

Occasionally, because of their fine sandy texture, dried tailings have been used for construction of homes or for landfills. In homes built on or from such material, high levels of gamma radiation and radon were found. The US Environmental Protection Agency (EPA) estimated the lifetime excess lung cancer risk of residents of such homes at 4 cases per 100.

Reclamation of old uranium mines

In the early years of uranium mining after World War II, the mining companies often left sites without cleaning up after the ore deposits were exhausted: often, in the United States, not even the mine openings were secured, not to mention reclamation of the wastes produced; in Canada, uranium mill tailings were often simply dumped in nearby lakes.

In Canada and the United States, there still exist hundreds of smaller legacy uranium mines where no reclamation has taken place at all. In some instances, governments are still trying to identify current owners who can be held responsible for reclamation, and from time to time some government agency reclaims a site on its own account (or at least makes an announcement to do so). An example of a successful mine reclamation is that of the large Jackpile Paguate mine in New Mexico. Considerable effort has also been spent for the reclamation of the large Wismut uranium mines in eastern Germany, which is nearing completion now.

Cleanup is not only necessary for disused conventional mines, but also after termination of in-situ leach operations: the waste slurries produced must be safely disposed of, and the groundwater, contaminated from the leaching activities, must be restored. Groundwater restoration is a very tedious process, and it is not possible to restore its quality to previous conditions, although sophisticated pump and treatment schemes have been applied. In the United States, restoration efforts have been halted in many cases, after years of pumping and water treatment resulted in insufficient decreases of contaminant loads. The site-specific cleanup standards have been rather relaxed, then. While these sites are mostly located in remote areas and where groundwater is hardly potable anyway, vast legacy sites were left in densely populated areas from in-situ leach mining performed for the former Soviet Union: restoration programs are underway in Germany and the Czech Republic, but the sites in Bulgaria were simply abandoned.

Uranium mill tailings are in most cases disposed of in some form or another, to limit contaminant release into the environment. The obvious idea of bringing the tailings back to where the ore has been taken from does not necessarily lead to an acceptable solution for tailings disposal. Although most of the uranium was extracted from the material, it has not become less hazardous: quite to the contrary. Most of the contaminants (85 percent of the total radioactivity and all the chemical contaminants) are still present, and the material has been brought by mechanical and chemical processes to a condition where the contaminants are much more mobile and thus susceptible to migration into the environment. Therefore, dumping the tailings in an underground mine cannot be afforded in most cases; there, they would be in direct contact with groundwater after halting the pumps.

The situation is similar for deposit of tailings in former open-pit mines. Here also, immediate contact with groundwater exists in many cases, or seepage presents risks of contamination of groundwater. An advantage of in-pit deposition is its relatively good protection from erosion, though. In most cases, tailings have to be dumped on the surface for lack of other options. Here, the protection requirements can more easily be controlled by appropriate methods, but additional measures have to be taken to assure protection from erosion.

In the United States, detailed regulations for tailings disposal were promulgated by the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC) in the 1980s. These regulations not only define maximum contaminant concentrations for soils and admissible contaminant releases (in particular for radon), but also the period of time, in which the reclamation measures taken must be effective: 200 to 1000 years, preferably without active maintenance. Based on these regulations, more than a dozen of legacy tailings sites have been reclaimed, partly on location by smoothing slopes and applying multi-layer earthen and rock covers, and partly through relocation whereby the tailings were moved to more suitable places to avoid hazards of flooding or groundwater contamination.
In Canada, on the contrary, the measures taken for the reclamation of uranium mill tailings are much less stringent; for the large tailings in the Elliot Lake area, Ontario, for example, the measures include a water cover as the only “protective barrier.” For the tailings generated from uranium mining on behalf of the former Soviet Union, the situation is quite varied: while the tailings in eastern Germany, Hungary, and Estonia are currently being reclaimed in place, those in the Czech Republic, Ukraine, Kazakhstan, and Kyrgyzstan, among others, are still awaiting protective action. The 100 million t tailings in Aktau, Kazakhstan, have not even been equipped with a provisional cover; so, large amounts of dust continue to be blown into the neighborhood. The Kyrgyz tailings are located on steep valley slopes and are highly endangered by landslides.

The cost of tailings reclamation spans an extremely wide range. At the top end stands the cost incurred for the government-run large-scale reclamation of legacy tailings in the United States and Germany. If the reclamation cost is attributed to the uranium originally produced at these sites, then it corresponds to approximately US$14 per lb U_3O_8 produced, in both cases. This figure is higher than the price of fresh uranium used to be for several years, before the recent price rally began. The low end of the cost range (for mines with uranium as the primary product) is marked by Canada’s US$0.12 per lb U_3O_8 produced; this reflects the extraordinarily poor environmental standard applied in Elliot Lake.

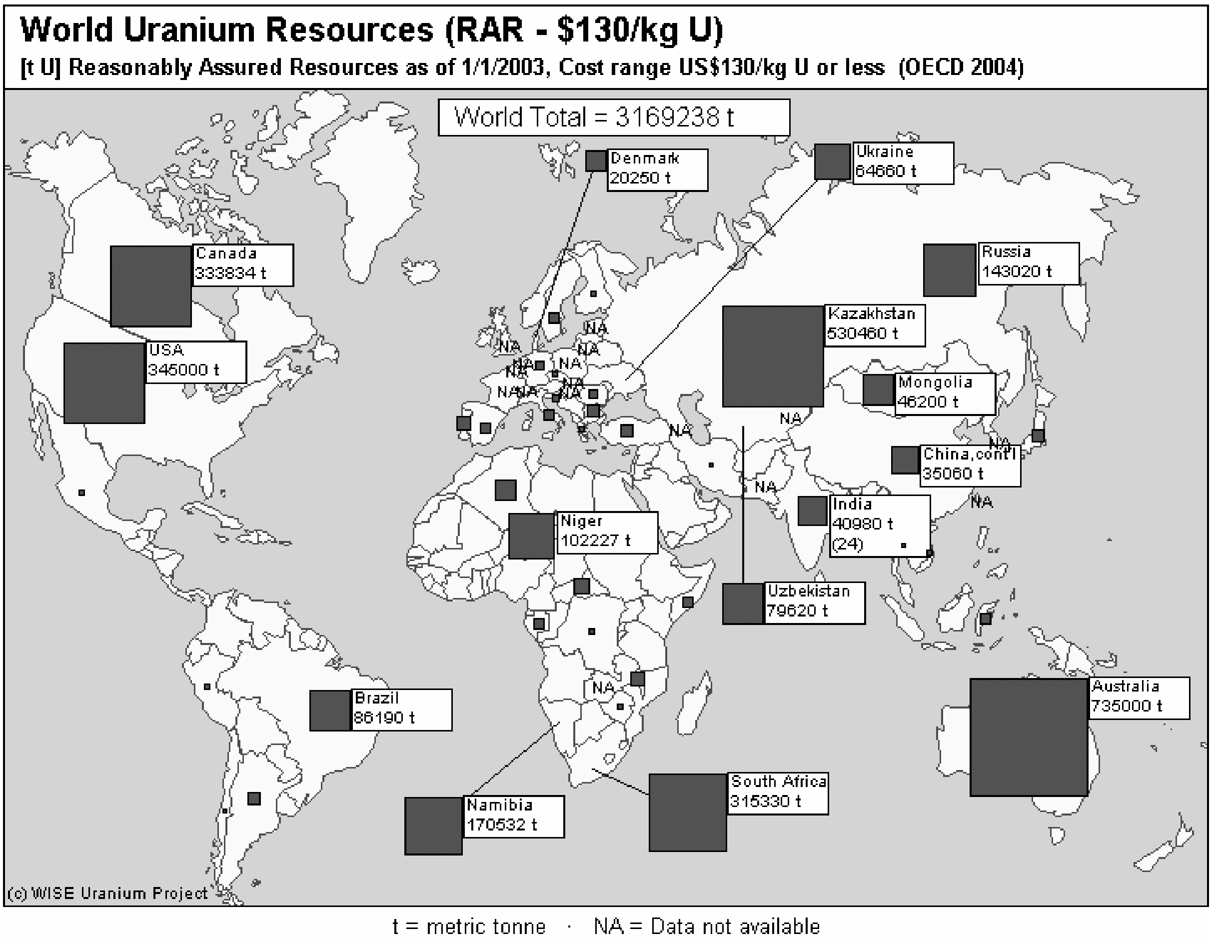
To avoid generation of further uranium mining legacy sites that eventually have to be cleaned with tax money, current commercial uranium miners have to deposit decommissioning funds when they start mining. But even this procedure cannot prevent the taxpayer from being tapped as a last resource: the funds set aside for the cleanup of the now bankrupt Atlas Corp’s uranium mill tailings in Moab, Utah, for example, make up for just three percent of the reclamation cost of US$300 million now actually expected. And, in Australia, it became known only recently that the closure of the major Ranger Mine is to cost A$176 million, of which only A$65 million is covered by a guarantee. In case Ranger operator ERA would go bankrupt, the taxpayer would have to supply the major portion of the reclamation cost . . .

Uranium resources

Primary resources

Uranium deposits are usually classified according to the degree of confidence gained on the size of the ore deposit, and the expected recovery cost. According to the authoritative “Red Book” (NEA 2004), the “known resources” recoverable at costs of up to US$130/kg uranium (equivalent to US$50/lb U_3O_8) amount to approximately 4.6 million t uranium worldwide. Furthermore, so-called “undiscovered resources” recoverable at the same costs are estimated at 6.7 million t uranium, plus 3.1 million t uranium without cost range assigned. Since the “undiscovered resources”—as their name already suggests—are rather speculative figures, further discussion will be limited to the “known resources,” comprising the categories RAR (Reasonably Assured Resources) and EAR I (Estimated Additional Resources I). Fig. 2 shows a world map of the Reasonably Assured Resources recoverable at costs of up to US$130/kg uranium (WUP 2005).

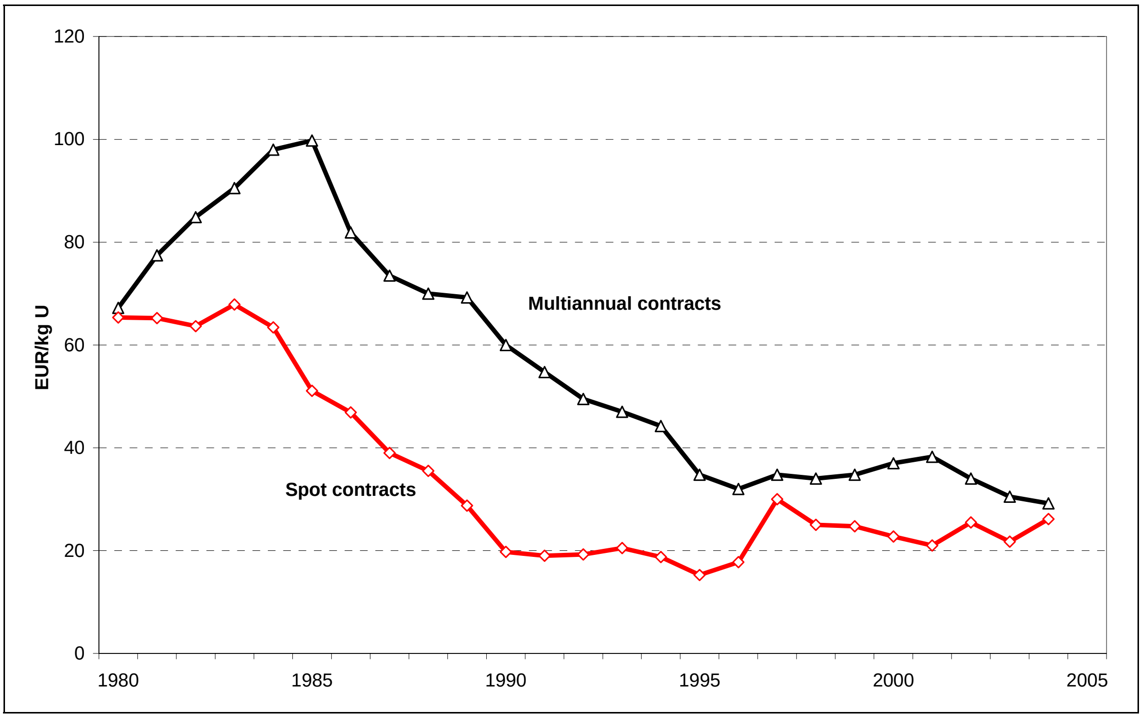
Fig. 2.



Uranium, unlike many other raw materials, is found in deposits on all continents. But, very few countries host the vast majority of the known uranium resources, in particular when focusing on the resources contained in high-grade deposits and/or recoverability at low cost.

After having reached a peak of approximately US$43/lb U_3O_8 at the end of the 1970s, the uranium spot market price soon leveled off to approximately US$10/lb U_3O_8. At the end of 2000, it even dropped to a low of approximately US$7/lb U_3O_8, but then started climbing again, reaching US$33/lb U_3O_8 on October 10, 2005. The average prices paid for uranium delivered under spot and multiannual contracts to European utilities from 1980 to 2004 are shown in Fig. (ESA 2005).

Fig. 3. Euratom Supply Agency Uranium Prices



During the two decades of depressed uranium prices, uranium exploration efforts declined to a minimum. But now, they are on the rise again, in particular since the uranium spot market price reached US$20/lb U_3O_8 in September 2004; many exploration companies have newly formed or have changed their focus to uranium. As a result, new findings may increase the amount of known resources. While new discoveries of high-grade and large-scale deposits are not impossible, it is more likely though that many current efforts will identify smaller low-grade deposits. Only in one case, Shea Creek in Saskatchewan, Canada, has a new high-grade deposit possibly been discovered, the first one in around twenty years.

Several uranium deposits are currently unavailable for mining due to political opposition. The most prominent example is that of the major Jabiluka deposit in

Australia's Northern Territory. The site is surrounded by, but excised from, World Heritage-listed Kakadu National Park. Due to the continued opposition from the Traditional Owners, operator ERA had to stop the development of the deposit and to backfill a decline that had already been driven into the deposit. Another example is that of the Crownpoint in-situ leach project in New Mexico. This project, located on Navajo land, had its license put on hold in May 2000 on request from local intervenors. Meanwhile, the Navajo Council passed legislation banning all uranium mining and processing on Navajo land. The law came into effect on April 29, 2005, but may be superseded by federal law.

Cogéma's McClean Lake mine in Saskatchewan, Canada, had its license revoked in September 2002 by a court decision at the request of a local environmental organization, but the company was soon after granted a stay and finally won its case in March 2005.

The proposed new uranium mines in the Indian states of Jharkhand, Andhra Pradesh, and Meghalaya are currently facing heavy opposition from local tribal and environmental groups.

Opposition to uranium mining is not limited to environmental organizations or indigenous people: in Australia, three state governments (Queensland, Victoria, and Western Australia) have banned uranium mining. This does not deter venturesome exploration companies from continuing their work in these states, though. They apparently are hoping for a revision of these states' policies, aware of the fact that the current federal government is very supportive of uranium mining.

In addition to those deposits where uranium is being mined as the principal resource, there exist several types of deposits where uranium is only a **by-product** of mining performed for other minerals, such as gold, copper, or phosphate.

In South Africa, all uranium is recovered as a by-product of gold mining. Given the unfavorable exchange rate of the local currency and the recent low of the uranium price, however, there is currently only one gold mine (Vaal River) operating uranium extraction circuits. In addition, the poor profitability of many South African gold mines may entail the shutdown of marginal mines, also decreasing the potential for future by-product uranium extraction.

The Olympic Dam mine in Australia is exploiting a very large ore body for copper. Uranium is being extracted as a co-product. In spite of the low uranium grade of 0.053 percent U, the total uranium resource amounts to 302,000 t U, making it the largest single uranium deposit in the world. Recent proposals foresee a capacity expansion in order to more than double the mine's annual output.

Phosphate rock has an average uranium content of 0.005 to 0.02 percent. The potential uranium content of known phosphate rock world-reserves is in the range of 5 to 15 million t uranium (this figure is not contained in the resource estimates reported above). Major deposits are located in Morocco, the United States, Mexico, and Jordan. The widely used phosphoric acid process concentrates most of the uranium in the product stream (fertilizers, etc.). Various technologies exist to recover the uranium from the product stream, thus removing this undesired constituent from the products and providing an alternate source of uranium. Worldwide, there are approximately 400 wet-process phosphoric acid plants in operation from which some 11,000 t U could in principle be recovered each year. While a number of uranium recovery plants have been built in countries such as the United States, Canada, Spain, Belgium, Israel, and Taiwan, most of these have been shut down during the recent depression of uranium prices, but their restart could become economical again with rising prices of uranium.

Moreover, several types of large **marginal uranium deposits** are not included in the world uranium resource estimates, the most prominent ones being located in black shale. Black shale deposits contain only 0.005 to 0.04 percent of uranium, but because of their large areal extent they contain very large uranium resources, such as 169,230 t in Ronneburg (Germany), 254,000 t in Ranstad (Sweden), and 4 to 5 million t in Chattanooga Shale in the United States, for example. But, even the promoters of nuclear power appear to be uncertain whether these deposits can ever be mined: “While the black shale deposits represent a large resource, they will require very high production costs, and their development would require huge mines, processing plants and mill tailings dams, which would certainly elicit strong environmental opposition. In addition, the Ronneburg area is currently the subject of the multibillion dollar Wismut reclamation project. Therefore the black shale deposits represent a long term resource that will require market prices in excess of US$130/kg U to be economically attractive, assuming environmental opposition could be overcome, which is by no means certain for any of the three deposits mentioned above,” (IAEA 2001).
Another potential uranium resource discussed from time to time is **seawater**: it contains uranium at just 3 mg/t, but the total resource is estimated at 4 billion t. Research on an improved extraction technology is ongoing, but so far, it is not competitive at current or foreseeable uranium prices, and its energy and environmental balance has not been assessed yet.

Secondary resources

Secondary resources are those derived in places other than in ore deposits. They comprise of uranium recycled from various sources, such as from spent fuel, surplus weapons uranium, and depleted uranium tails, plus uranium from stock holdings.

Recycled uranium from spent fuel (RepU): Recovery of uranium from spent fuel currently takes place mainly at the La Hague (France) and Sellafield (United Kingdom) reprocessing plants. However, to date, only a minor fraction of the separated uranium has actually been recycled into new fuel. And, apparently, there are no expectations that this may change in the near future:
In France, utility Electricité de France (EdF) has made provisions for long-term storage of the reprocessed uranium (RepU) for 250 years, as was revealed in a recent report of the French Court of Auditors. Of the 1050 t of spent uranium oxide fuel annually generated in France, 850 t are being reprocessed at La Hague, at present. (In addition, 100 t of spent MOX fuel arise, which are not reprocessed at all.) From reprocessing of uranium oxide fuel, approximately 816 t of uranium and 8.5 t of plutonium are recovered. Of the uranium recovered, approximately 650 t are converted to the more stable oxide form for long-term storage to await future use. The uranium recovered in the former Marcoule reprocessing plant has never been recycled into nuclear fuel at all. It still stays at Marcoule, in the liquid form of uranyl nitrate: 3800 t owned by EdF, and 4800 t owned by CEA and Cogéma.
Usage of reprocessed uranium is problematic for several reasons. Since the RepU is contaminated with the artificial uranium isotopes U-232 and U-236, special precautions

are necessary during processing: the U-232 and its decay products cause elevated radiation doses for the plant personnel, and the U-236, as a neutron absorber, requires higher enrichment levels to achieve the same reactivity. As a consequence, use of the RepU is not very attractive at present market conditions: conversion is three times more expensive than conversion of natural uranium, and enrichment cannot be done in France's sole enrichment plant (Eurodif gaseous diffusion plant), since the RepU would contaminate the plant's circuits. For production of two test refueling batches for the Cruas nuclear power plant, the RepU was enriched in a foreign (presumably Russian) centrifuge enrichment plant.

Downblended HEU: Highly enriched uranium (HEU) from surplus nuclear weapons can be blended down to low-enriched uranium (LEU) for use in nuclear fuel.
In 1993, the United States and Russia concluded the US-Russia HEU Agreement, under which Russia was to supply the downblended uranium derived from 500 t of HEU to the United States over a period of about twenty years. This amount of HEU represents the equivalent of 153,000 t natural uranium and an enrichment work of 92 million SWU (Separative Work Units).
The deliveries under this agreement (LEU derived from approximately 30 t HEU annually, replacing approximately 9000 t Unat) are still ongoing and will continue until 2013.
Meanwhile, the United States has begun downblending some of their own surplus HEU. A total of 153 t HEU has been designated for downblending; approximately 39 t have already been processed, and this processing is expected to be completed by 2016. (NEA 2004)
Unfortunately the HEU is not only high in U-235, but also in the undesired nuclide U-234. If diluted with natural uranium, residual U-234 concentrations in the blended LEU product may exceed industry specifications for nuclear fuel. It is therefore advisable to blend the HEU with some material low in U-234.
In Russia, this problem is solved by producing a blendstock with an assay of 1.5 percent U-235 by tails enrichment, that is, surplus centrifuge enrichment capacities are used to re-enrich depleted uranium tails to an U-235 assay of 1.5 percent. This approach further enables Russia to fulfil its obligations under the US-Russia HEU agreement, without having to touch its scarce natural uranium sources. Most remarkably, the separative work spent for blendstock enrichment in this case is larger than that recovered in the HEU blending process, (Diehl 2004). The enormous amount of separative work originally spent for the HEU production thus is completely lost; only the uranium feed contained in the HEU is recovered.

Uranium from tails enrichment: The waste arising from enrichment of uranium is called depleted uranium (DU) or tails. It has the chemical form of uranium hexafluoride (UF_6) and still contains some residual amounts of the fissile uranium isotope U-235 that can be extracted by further enrichment. Since 1996, depleted uranium tails from West European enrichers Urenco and Eurodif are being sent to Russia for re-enrichment. In Russia, instead of natural uranium, the imported tails are fed into surplus enrichment cascades owned by Rosatom—the Russian Federal Atomic Energy Agency (previously Minatom). The product obtained from re-enrichment is mostly natural-equivalent uranium plus some reactor-grade low-enriched uranium (LEU). These products are sent back to Urenco and Eurodif, while the secondary tails generated remain in Russia, where they are re-enriched further to obtain more natural-equivalent uranium and/or slightly enriched uranium. The latter is then used as blendstock for the downblending of surplus weapons-grade highly-enriched uranium (HEU) into reactor-grade low-enriched uranium (LEU). The ultimate tails left, still comprising at least two-thirds of the amount imported, remain in Russia with, thusfar, an unknown fate. In May 2005, Cogéma/Areva announced that it had signed a technology transfer agreement with Russia's Tenex for the defluorination technology used to de-convert depleted uranium hexafluoride (UF_6) to U_3O_8—a form more suitable for long-term storage. And, in August 2005, Rosatom declared that the ultimate tails can be used in fast neutron reactors (!).

At present, Urenco and Eurodif each send 7000 t U in tails per year to Russia for re-enrichment, and, Urenco and Eurodif each get back 1100 t U of re-enriched natural-equivalent uranium contained in UF_6. Eurodif, in addition, gets back 130 t U in UF_6 of uranium re-enriched to 3.5 percent. For Urenco and Eurodif, the re-enrichment deal is primarily of interest for the avoided tails disposal cost. For Rosatom, it presents an opportunity to use its surplus centrifuge enrichment capacities. Urenco assumes that the re-enrichment contract with Russia is to cease after 2010. Details on the re-enrichment business can be found in Diehl (Diehl 2004).

If the uranium price increases further, enrichment companies might anyway consider to lower their tails assays, that is, the residual concentration of U-235 in the depleted uranium tails left from enrichment. They could thus reduce the demand for uranium at the expense of additional enrichment work. The same amount of enriched uranium could then be produced at a lower consumption of natural uranium.

Uranium from stock holdings of natural and low-enriched uranium: Only scarce information is available on the stockholdings in low-enriched and natural uranium in the world. This is one of the reasons why there is so much uncertainty about the future of the uranium market. The natural uranium stocks amount to 41,633 t, and the enriched uranium stocks could replace 23,440 t of natural uranium (NEA 2004); but these figures are highly unreliable since no information is available from most countries.

Substitution of uranium

The lifespan of uranium resources may be prolonged by the use of other fissile materials, such as plutonium, or the artificial uranium isotope U-233, which can be obtained by irradiation of thorium.

Plutonium (MOX fuel): Regarding fuel to be used in light-water reactors, some of the fissile uranium isotope U-235 can be replaced by the plutonium isotope Pu-239. For this purpose, plutonium is blended with natural or slightly enriched uranium to produce a mixed oxide (MOX) fuel. Plutonium is available from surplus weapons plutonium and as recycled plutonium obtained from reprocessing of spent fuel. The Center for International Security and Cooperation at Stanford University estimates the total amount of excess military plutonium available at 92 t, which could replace 11,040 t natural uranium, and the amount of civilian plutonium at 252 t, which could replace 30,240 t natural uranium. Several aspects of MOX fuel continue to cause political opposition, though, in particular the hazards and environmental impacts of the reprocessing of spent fuel and the need to transport plutonium over large distances.

In September 2000, the United States and Russia concluded a surplus plutonium disposition agreement, according to which they will dispose of 34 t of excess weapons-grade plutonium each during the next twenty-five years by producing MOX fuel. For this purpose, the United States is planning to build a MOX fuel plant at the Savannah River site in South Carolina, while the Russian plant is to be built at Seversk. Some first test fuel assemblies with US plutonium were manufactured at Cadarache and Marcoule in France and delivered for testing at the Catawba nuclear station in South Carolina in April 2005.

The plutonium generated by neutron activation of U-238 in the fuel of commercial reactors can be recovered by treatment of the spent fuel in a reprocessing plant. So far, such reprocessing mainly takes place in Europe, in La Hague (France) and Sellafield (United Kingdom), and only some fraction of all spent fuel is being reprocessed. In addition to the environmental problems connected to it, the process of reprocessing is also subject to several limitations: the only spent fuel suitable for reprocessing is that which was mostly made from fresh uranium, since otherwise unwanted isotopes and elements would contaminate the separated plutonium. In 2003, EU utilities (and these are the major consumers of MOX fuel so far) used MOX fuel containing 12.12 t Pu, replacing 1450 t natural uranium and an enrichment work of 0.97 million SWU.

Thorium: India, a country hosting only poor uranium deposits but large thorium sand deposits, and possibly other countries, are considering establishing a thorium-based fuel cycle. Thorium (Th-232) itself is not fissile and thus cannot sustain a nuclear chain reaction, but when subject to neutron radiation, it transforms (through neutron activation to Th-233 and subsequent decay via Pa-233) into the fissile uranium isotope U-233, which can be used for reactor fuel. The process requires, however, a strong neutron source, that means a uranium- or plutonium-fueled nuclear reactor, to irradiate the thorium. Thorium thus cannot eliminate the need for uranium, it only reduces the uranium requirements. The U-233 produced could either be recovered by reprocessing and then be manufactured into fuel, or it could be burnt in place when it forms. The thorium fuel cycle presents serious technological challenges, however, since irradiated thorium fuel hardly dissolves in HNO_3 (required for reprocessing), and U-233 presents a serious radiation hazard due to the presence of U-232 and its strong gamma-emitting decay products.

Thorium-based prototype reactors (AVR in Jülich, and THTR 300 in Hamm-Uentrop, Germany) had to be shut down after experiencing continued technical problems. Their fuel was made from thorium and highly enriched (!) uranium, embedded in a graphite matrix.

Even if the technological challenges of the thorium fuel cycle could be overcome, there would remain the problem that the thorium deposits are also limited and their exploitation would affect the environment as well.

South Africa is planning to establish a fuel cycle for the Pebble Bed Modular Reactor (PBMR). However, this reactor type, though being a derivative of the THTR, appears to be a purely uranium-fueled reactor with no thorium involved.

Summary of Uranium Resources

The world uranium resources can be summarized as follows: Known primary resources (recoverable at costs of up to US$130/kg uranium) comprise 4.6 million t uranium. Secondary resources from stocks in various forms add another 0.21 million t natural uranium equivalent, that’s just 5 percent. For recycling of uranium from spent fuel and re-enrichment of tails, no “resource” can be easily identified; only production rates can be determined, based on available processing capacities. In addition, plutonium could replace 0.04 million t natural uranium.

Uranium supply and demand

In 2003, worldwide uranium production capacity from mines was 47,260 t uranium, while production actually reached only 35,772 t uranium, that is 76 percent of the capacity. On the other hand, nuclear power-related uranium consumption in the same year was 68,435 t uranium. Production from mines thus supplied just 52 percent of the demand, the large remainder came from secondary resources. Given that the secondary resources will expire in less than ten years, uranium production from mines will have to nearly double to meet the demand at current levels. This means that many new mines have to be constructed, since such a production increase cannot be sustained by the current capacities. Major production increases are not possible on short notice, however, since the development of new mines requires time spans of ten years or more. In addition, there are only very few deposits ready for development now, since exploration efforts had decreased to a minimum during the past two decades of low uranium prices. And since the known uranium resources in high-grade deposits are very limited, any major increase in uranium production would have to rely on the mining of low-grade deposits, involving very large-sized operations with enormous environmental impacts. This production capacity bottleneck may even become more serious, if certain proposals for an expansion of nuclear power are realized.

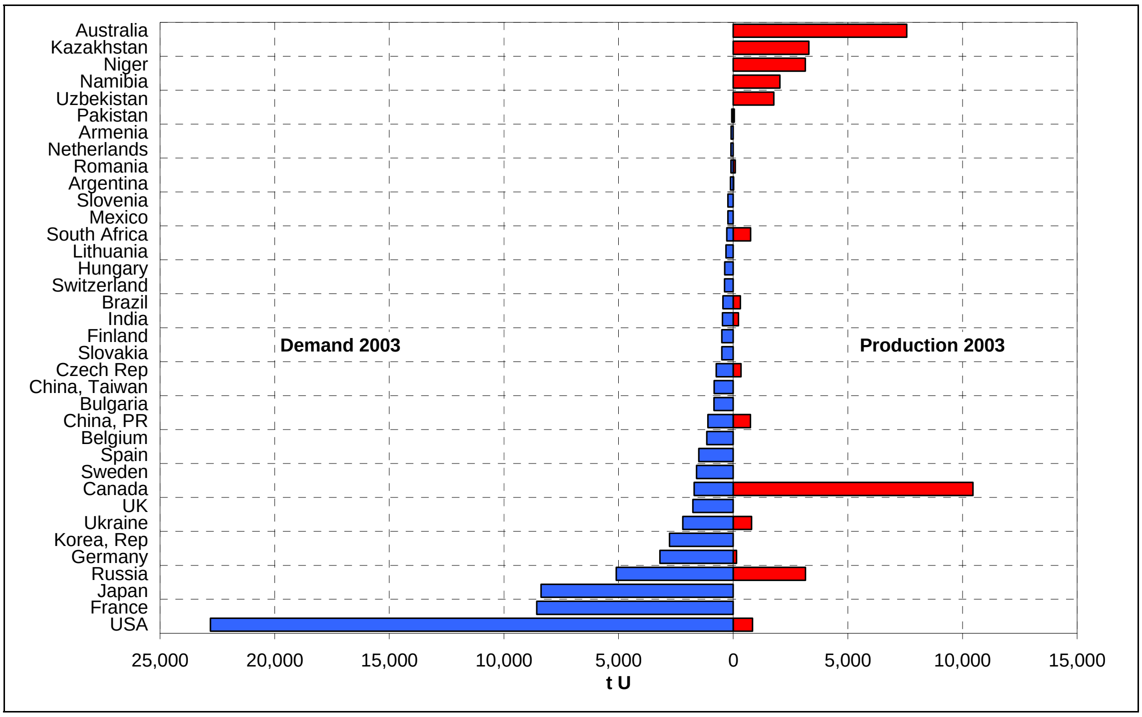
Table 1. Annual uranium production by country in 2003 (WNA 2005)

Rank	Country	t U	% of World	Notes
1.	Canada	10457	29.2%	
2.	Australia	7572	21.2%	
3.	Kazakhstan	3300	9.2%	
4.	Russia	3150	8.8%	c)
5.	Niger	3143	8.8%	
6.	Namibia	2036	5.7%	
7.	Uzbekistan	1770	4.9%	
8.	United States	846	2.4%	
9.	Ukraine	800	2.2%	c)
10.	South Africa	758	2.1%	a)
11.	China, cont’l	750	2.1%	c)
12.	Czech Rep.	345	1.0%	
13.	Brazil	310	0.9%	
14.	India	230	0.6%	c)
15.	Germany	150	0.4%	b)
16.	Romania	90	0.3%	c)
17.	Pakistan	45	0.1%	c)
18.	Argentina	20	0.1%	
	World Total	**35772**	**100.0%**	

a) Uranium is by-product of gold mining
b) Production from decommissioning
c) WNA estimate

Another aspect is the regional imbalance of supply and demand. No consumer country, except for Canada and South Africa, can meet its uranium demand from domestic production. And most current large-scale consumers, except for the United States and Russia, only have minor uranium resources, if any at all. Only seven countries produce more uranium than needed for their domestic demand (if one exists), see Fig. 4 (NEA 2004).

Fig. 4. Uranium Demand and Production 2003 t/U



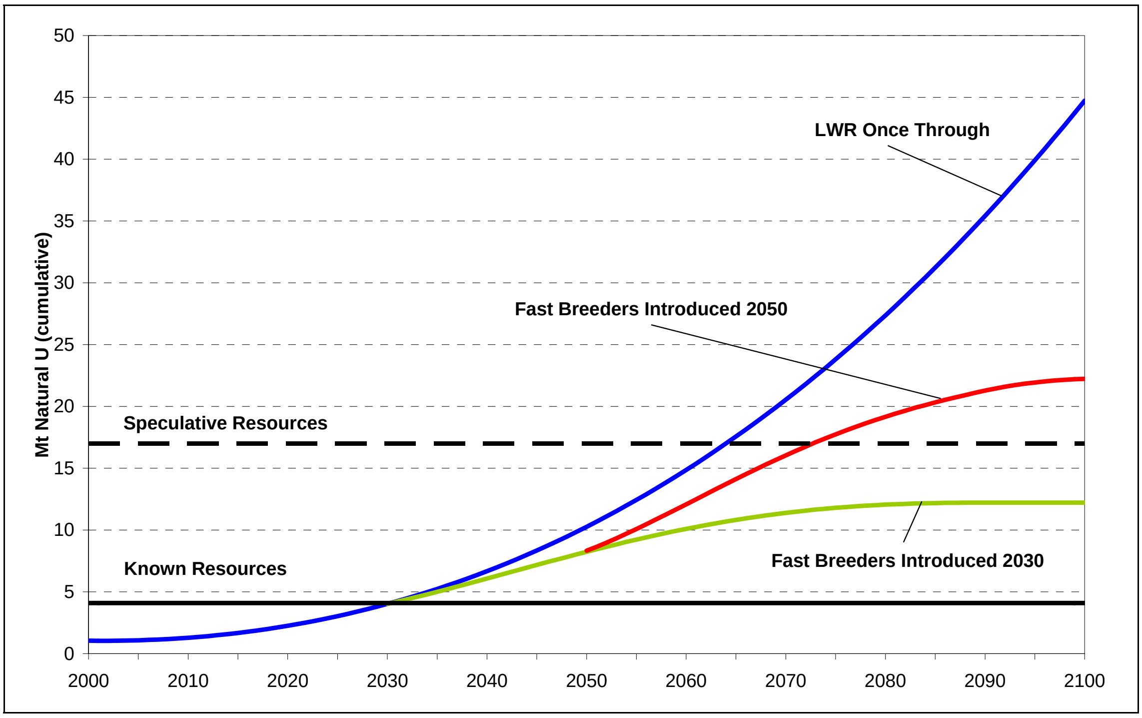
Particularly serious is the uranium supply situation of Russia: Since the dissolution of the Soviet Union, Russia has been cut off from major uranium resources, mainly in Kazakhstan. At the current production rate of 3150 t/a (2003), Russia's reserves that are mineable at current uranium prices will be mined out in just fifteen years. Moreover, Russia's annual reactor-related uranium requirements of 5100 t U (as of 2003) exceed the domestic production by 1950 t U, or 62 percent. In addition, Russia has plans to build several new reactors. So, unless Russia holds major uranium stocks, it will run into a serious uranium supply crisis in rather short time. Russian officials now even propose to mine large, uneconomical low-grade deposits in Yakutia—just to get any uranium at all. Russia's urgency to get at uranium feed may also explain the surprising fact that Russia spends more enrichment work to process imported depleted uranium tails into blendstock for HEU downblending, than is recoverable from the blended low-enriched uranium obtained (see above). Using surplus enrichment capacities, Russia in this way recovers urgently needed secondary uranium supplies from imported tails, waving the chance to recover enrichment work originally spent for HEU.

This looming Russian uranium supply gap is of particular interest to European Union (EU) utilities, since Russian material from natural uranium (3400 t U), re-enriched tails (1000 t U), and downblended HEU (1300 t U) combined accounted for 35 percent of the total deliveries to EU utilities in 2003.

India and China both intend to set up major nuclear power programs and thus are potential large-scale consumers of uranium. However, both only dispose of very limited uranium deposits.
India, being a non-signatory to the Nuclear Non-Proliferation Treaty (NPT), has no access to foreign uranium resources after having conducted a nuclear weapon test in 1974. India's own uranium resources, though, are only small and low-grade. But having no other option, India is currently planning to develop new mines on low-grade deposits in several parts of the country—against furious tribal and environmental opposition. India's efforts to set up a thorium-based nuclear fuel cycle must also be seen in this context. Meanwhile there are some indications, however, that India is considering to find some political solution to this dilemma: As a first step, India ratified on March 31, 2005, the Convention on Nuclear Safety (CNS), which opens Indian nuclear power plants to outside peer reviews.
China would like to import uranium from Australia, but the safeguard obligations for Australian uranium prevent such exports to China, so far. China is not willing to accept IAEA inspections to verify that its nuclear power program serves exclusively peaceful purposes. Nevertheless, in February 2005, China and Australia started talks aimed at making such exports possible, in their mutual interest.

But even if the problems of production capacity bottleneck and regional imbalances could be overcome, another aspect has to be kept in mind: the lifespan of the known uranium resources. The known primary and secondary resources could supply current demand for seventy years. However, new reactors currently being commissioned will increase demand. Fig. 5 shows the worldwide uranium resource utilization based on the assumption that nuclear energy would maintain its current market share with a rising total electricity production (NERAC 2002). For this scenario and the utilization of uranium in a once-through cycle (without reprocessing) in light-water reactors, the known uranium resources would expire by approximately 2030, and the speculative resources by approximately 2060. Therefore, nuclear power could only run on, if more and more low-grade and marginal uranium deposits would be mined—at high environmental and monetary cost.
The limitations of the known uranium resources could only be overcome by massive use of fast breeder reactors. The fast breeder technology once promised to extend the lifespan of the uranium resources by a factor of up to 60. However, technical problems have caused the shutdown of all prototype reactors, except for one in Russia. Russia and China still consider this technology a viable option to solve their power supply needs, though.

Fig. 5. Worldwide Uranium Resource Utilization



Conclusions

Uranium mining expanding, while legacies not managed

- The current revival of the uranium mining industry is going to produce new environmental hazards and liabilities, while those legacies left from the Cold War era still haven't been dealt with accordingly in many countries.

Known resources insufficient to meet increasing demand

- Known resources in ore deposits are only capable of supplying projected demand without reprocessing until approximately 2030, while speculative resources would expire by around 2060. Therefore, mining will increasingly have to be done on low-grade and marginal ores, involving vast environmental impacts.
- Secondary resources, though currently supplying nearly half of the demand, make up for only approximately 5 percent of total resources.

Lack of mining capacities

- Mining output has to be doubled within approximately ten years, just to meet demand at the current level, since secondary resources are going to be exhausted. But, existing mining capacities cannot meet this demand, and very few mines are ready for development, at present, while start-up times of new mines are long.

- Any increase in demand would require a further major increase of mining capacities.

Regional imbalances of supply and demand

- Most current and potential major consumer countries own very little domestic uranium resources and will have to rely on uranium imports, therefore, while just seven countries produce enough uranium to export any at all.
- Particularly precarious is the situation of Russia, which faces a severe supply crisis within a decade. This crisis will also have impacts on the uranium supply to the EU, which currently is highly dependent on deliveries from Russia.
- Supply problems will increase dramatically if India and China, while hosting only negligible uranium resources, actually choose to develop nuclear power on a large scale.
- In addition, safeguard problems are incurred with potential uranium exports to Russia, India, and China.

3 Nuclear Waste Management

Transportation

Without the transportation of radioactive materials there can be no use of nuclear energy because transports are the links between the single stages of the nuclear fuel cycle. Examples of transported materials are milled uranium, uranium hexafluoride, fresh and spent fuel elements, and many kinds of waste. Worldwide some 100,000 transports for the use of nuclear power were done every year; in Germany this averages to about 10,000 transports per year. A portion of transports covers long distances, for example uranium hexafluoride from Germany to Russia (some 1,000 km by land) or plutonium containing material from a reprocessing plant in France to Japan (more than 15,000 nautical miles by sea). There are some places where a concentration of such transports occur, such as reprocessing facilities, interim storage facilities, or harbors. In the interest of residents and transport workers, it should be ensured that, for safety measures, this concentration of transports is well thought-out, especially with regard to radiation exposure by incident-free transports as well as the possibility of accidents. In most countries only the single transport is looked for. Many transports take place only for economic reasons. For example, German power plants are supplied with fuel made in Sweden whereas Swedish power plants are supplied with fuel made in Germany.

For the transportation of radioactive materials, recommendations are given by the International Atomic Energy Agency (IAEA 1995). The aim of the regulations is to reduce the dangers to an “acceptable” level. Safety philosophy is based on the packaging for the radioactive material. The requirements for the robustness of the packaging depend on the radioactive inventory. For transports with very high-active material, the cask should be able to withstand severe accidents. Among other things, robustness is defined as withstanding a drop from a height of 9 m on a flat unyielding target, a drop from a height of 1 m onto a steel bar, a fire of 800°C for a period of 30 minutes, and an immersion in 15 m deep water for 8 hours. These definitions are often criticized because package design for these standards may result in a certain safety for many real accident situations, but all the factors which may come to bear on the package during a severe (still plausible) accident would not be covered. For example, an impact of a package with a transport velocity of 80 km/h on rocky ground or a package in a tunnel fire for a period of 30 minutes will exceed the requirements. In these cases, a release of radionuclides would take place and a strong exposure to radiation in the population is possible.

In recent years, there were only a small number of accidents during transports within the so-called fuel cycle of nuclear power plants. No notable releases of radioactive material were published. However, it should be stated that the integral number of transports will increase greatly when new nuclear power plants, final repositories, or other new facilities of the nuclear fuel cycle go into operation in some countries. It is fortunate that no severe accidents have taken place up to now. But it is possible with every transport.

No absolute safety for the transport of radioactive material is possible. This is true for incident-free transport, as well as for accidents. There is no effective protection of transports and packages against terrorist attacks. Severe accidents or terrorist attacks during transports of high-active wastes, spent fuel, or plutonium dioxide can result in acute lethal doses in the immediate vicinity and long-term mortal doses within a few kilometers radius of the transport vehicle. The resettlement or evacuation of people living within several kilometers distance would be required (Large and Associates 2004).

Reprocessing of nuclear fuel

In the sixties and the early seventies of the last century, there was a dream: the never-ending business of nuclear power plants covering all energy needs in a cheap manner. Just like a "perpetuum mobilé" a nuclear fuel cycle should be created. Following the use of (fresh) uranium fuel in fission reactors in the main stages of this fuel cycle were planned the reprocessing of the used fuel with the separation of uranium and plutonium, the use of the separated fuel material in fast breeder reactors to multiply plutonium, a separation again by reprocessing, the reloading into a breeder, and a small part in fission reactors. The newly produced materials in the reactors should be reprocessed again, reloaded again, and so on. However, the dream is broken. Because of safety problems, small breed rates in experimental reactors, and high costs, the breeder development programs were abandoned in most countries, first in the United States in 1977, some years later in Germany, and again later in the United Kingdom and France. Today only Japan, Russia, and India have ambitions in the breeder sector. However, the development in these countries is snail-paced and far behind schedule. In addition to the described situation of fast breeder techniques, the main reason for reprocessing no longer exists. Without breeder technology, the continuous "recycling" of fuel is not possible. Nevertheless, a part of the nuclear industry and several governments decided to continue with reprocessing. They want to use the separated uranium and plutonium again in light-water reactors as mixed oxide fuel (MOX). Reprocessing plants are not operating in all of these countries. In Germany, the plans for a commercial plant were cancelled in 1989 because of safety discussions and economic reasons. German-spent fuel is reprocessed in France and the United Kingdom;[1] similarly Belgium, Switzerland, and some other countries on a smaller scale. The following reprocessing plants for the civil sector are in operation:

Table 2. Civil reprocessing plants in the world

Country	**Site**	**Capacity [MgHM]**
France	La Hague (UP2-800)	1,000
	La Hague (UP3)	1,000
United Kingdom	Sellafield (B205)	1,500
	Sellafield (THORP)	1,200

1 For the actual German situation, see Gruppe Ökologie (2005).

Russia	Chelyabinsk (RT1)	600
Japan	Tokai Mura (Tokai)	100
India	Tarapur (PREFRE)	400
	Kalpakkam (KARP)	100

Source: WISE-Paris

All capacity dates in the table are nominal—usually none of the plants achieve this output. In particular, it is known that the planned yearly capacity of THORP in Sellafield has never been achieved to date. It should be mentioned that additional military reprocessing takes place in France, the United Kingdom, Russia, and India, and that only military reprocessing is running in the United States and North Korea.

Reprocessing is a technically complicated and chemically complex process. The spent fuel assemblies are dismantled, the rods cut into pieces, and the pieces solved in nitric acid. After that, uranium and plutonium are separated and all material currents undergo further treatment. Four main material currents are produced through reprocessing:

- plutonium
- uranium
- low-, medium-, and high-active waste
- radioactive discharge with water and air

From eight spent uranium fuel elements, reprocessing produces one MOX fuel element and a lot of waste.

Plutonium/MOX

Nowadays the key element of civil reprocessing is plutonium. Regular spent fuel of light-water reactors contains about 1 percent plutonium. Theoretically, 5 to 6 Mg plutonium could be separated every year in the civil sector, if the above mentioned reprocessing capacities were used.

The plutonium should be completely fabricated in MOX fuel assemblies. In reality it is very difficult to realize this plan. Worldwide there exists only a small capacity to fabricate MOX fuel elements. A regular business on an industrial scale exists only in France and Belgium. The MOX fabrication plant in Sellafield has been in operation since 2001, but it doesn’t work well and there were some scandalous errors by personnel. Russia has no MOX fabrication plant and in Japan and India only small pilot plants are in operation. So it is an open question as to whether the complete recycling of plutonium will be possible. Treatments or conditioning for final disposal are not in development. It would be possible to immobilize plutonium in glass or ceramic.

The safety aspects and radiation protection of MOX fuel elements are to be evaluated even more critically than uranium elements:

- Plutonium has a high radiotoxicity. The inhalation of less than 0.1 mg of plutonium can be lethal.

- The criticality risk during the treatment and manufacture of plutonium is much higher than for uranium.
- There are a lot of possibilities for the release of plutonium in regular business during the reprocessing and manufacture of the oxide as well as in the case of accidents during reprocessing, storage, transportation, and treatment of plutonium, manufacture of mixed oxide, and the fabrication and transportation of MOX fuel elements.
- Light-water reactors are not initially designed to load plutonium containing fresh fuel in the core. The business with MOX is only possible by the reduction of technical safety margins (not as good steering of reactor, more difficult to switch off).
- With MOX fuel elements, the reactor-core inventory of long-lived radionuclides is higher. Therefore the radiological consequences are more hazardous.
- More heat generation and higher amounts of neutron radiation lead to increased problems during transportation, storage, and conditioning of the spent fuel.
- For current state-of-the-art facilities, MOX spent fuel cannot be reprocessed on an industrial scale. However, final disposal becomes more difficult because of heat generation, neutron radiation, and criticality. In comparison to the direct disposal of spent uranium fuel, a more complicated, more hazardous, and more expensive management—as well as an integrally larger repository volume—is necessary.

Uranium

Uranium takes about 99 percent of the heavy metal mass of spent fuel. In most countries, only a small part or nothing of the reprocessed uranium is recycled in civil reactors. It comprises only a small amount of fissionable uranium nuclides and more uranium nuclides with unpleasant radiation properties than natural uranium. A large part of the separated uranium is stored. In the past for some countries, uranium was sent to Russia for blending with high-enriched uranium from disarmed atom bombs. Requests for a smaller part of reprocessed uranium go toward shielding components, trim weights for airplanes, or penetration munitions. In summary, there is no real need for reprocessed uranium because no effective use in reactors is possible, and in other applications, activity-free materials should be used or the use should be forbidden (munitions for weapons). Plans for treatments or conditioning for final disposal are not in development.

Wastes

Originally in spent fuel, concentrated long-lived radionuclides (i.e., minor actinides) through reprocessing are distributed in different wastes with a wide range of radioactive inventory. Some waste is high-active and heat generating. In past years, the volume for the final disposal of radioactive material was increased by reprocessing with a factor of ten and higher. With regard to waste nowadays, this is true for all plants except La Hague, where for some kinds of wastes, a new conditioning method has recently been introduced.

All the wastes have to be treated and interim stored. This creates additional radiation exposures in incident-free business and additional risks for accidents. In particular, the high-active waste is stored in a hazardously liquid manner for long periods of time. In Sellafield, only a very small part of the waste produced by THORP has been vitrified since the beginning of operation in 1994. The pilot reprocessing plant WAK, in Germany, was closed in 1990; about 80 m^3 of high-active liquid waste has been stored in a pool up until now. The planned vitrification will drastically reduce the accident risks during storage and transportation. But radiation and heat generation are a further problem.

Discharges

Release of radionuclides during the dismantling and dissolving of the fuel assemblies, separation of uranium and plutonium, and treatment and storage of the waste is inevitable. In spite of filtering respectively other preventative measures, a portion of these radionuclides will be released with gaseous or liquid discharges in the environment around the reprocessing plants. Quantities of different radionuclides released annually by the reprocessing plants of Sellafield and La Hague are in the tens to thousands orders of magnitude higher than the discharges of a single light-water reactor (Marignac and Coeytaux 2003). People will be exposed through the radiation of contaminated ground, sediments, fauna, and flora. Following German regulations, both facilities would not be licensed because they exceed the limits (Öko-Institut 2000). In some investigations, different scientists note higher rates of leukemia for children (factor 3 in La Hague and factor 10 in Sellafield) in comparison with the average for the country. Definitive evidence for the connection between reprocessing and leukemia rates has not been given up to now, but it has also not been disproven. In the vicinity, high amounts of radioactivity in different birds and maritime animals were also measured. The levels exceed the limits of the European Union for the import of food.

Releases of reprocessing plants don’t just have a local impact on the environment. The liquid effluents are dispersed by the ocean current across a large area. Radionuclides from Sellafield have been measured on the coast of Ireland. Traditional fishing nations like Norway fear for their fishing areas in the arctic.

No benefit of reprocessing

The negative balance of reprocessing due to the arguments above can be supplemented:

- The targets of reprocessing in connection with light-water reactors have failed. The reprocessing of reused fuel in an industrial manner is not state-of-the-art yet. Therefore no economically significant savings of natural uranium is possible and no substantial reduction of plutonium inventory in waste for final disposal can take place. In a report for the French government in 2000, it was ascertained that reprocessing plus MOX could, in the best case scenario, only save around 10 percent in natural uranium needs and 15 percent of plutonium in final waste (Marignac and Coeytaux 2003).

- Severe accidents in reprocessing plants are not only theoretical. An actual example is the failure of a pipe which resulted in the release of 83 m^3 of dissolved spent fuel. Official publications said that there was no impact on the environment because the liquid was released in a sealed, contained area. The failure was not discovered for months, and it may be that only fortunate circumstances stopped any serious impact.
- In connection with the reprocessing of spent fuel, in La Hague every year there are about 450 shipments of plutonium or plutonium-containing materials. This amounts to more than 250,000 transport kilometers in France. These kilometers don't take into consideration the transportation of uranium and wastes. It is evident that a fuel cycle without reprocessing generally initiates significantly fewer transport kilometers.
- Reprocessing drastically increases the number of targets for terrorists. Besides transported packages, facility parts are targets with a great hazardous potential. In particular, an airplane crash into the storage pools for the spent fuel or liquid high-level waste, as well as into the storage building for separated plutonium would initiate catastrophic consequences which would exceed the Chernobyl accident. The release of radionuclides could be dramatically higher.
- Reprocessing is not an economic tool. A review of several studies for the German situation and of the OECD/NEA which compared a fuel cycle with reprocessing and a fuel cycle with "direct" disposal resulted in additional costs for reprocessing between 14 percent and 50 percent (Gruppe Ökologie 1998). New estimates for the United States showed an 80 percent increase in costs for a fuel cycle with reprocessing (Bunn et al. 2003). It should be mentioned that the assumptions in all studies seem in favor of reprocessing. Actually, the economic disadvantages should be more effective.

In summary, reprocessing offers no significant benefits in the so-called nuclear fuel cycle for safety, security, raw materials, and economic matters.

Interim storage

Independent of the nuclear fuel cycle concept (with or without reprocessing) interim storage of spent fuel and radioactive waste is necessary. For spent fuel and high-level waste, a longer storage time is required because the further treatment and, particularly, the final disposal, need an interim time to reduce heat generation and activity through the decay of short-lived nuclides. Low- and medium-level wastes have to be interim stored between the steps of treatment or conditioning until final disposal at least for logistical reasons.

For the storage of spent fuel, three concepts are in use (IAEA 1995):

- wet storage in water-filled pools

- dry storage in upright thick-walled casks
- dry storage in cans which are placed in vertical or horizontal shafts of reinforced concrete vaults

In only some cases are wet storage (in Sweden) and dry storage (in one of fourteen storage facilities in Germany) done underground. Dry storage concepts yield a lower possibility for incidents because there are no active systems for cooling, and the corrosion rate of the fuel cladding is probably lower. For this reason, and also because it is cheaper, in recent years dry storage in casks has mostly been preferred. On the other hand, mechanical impacts on the cladding are greater for dry storage and it must be ensured that the casks remain sealed for several decades. The long-term behavior is difficult to predict. It depends on the type of fuel, the type of cask, and modalities during the loading action. The time of experience for every specific case is relatively small. The storage facilities created thusfar often have no satisfying barrier against the release of radionuclides in regular business (wet storage) or have no satisfying surveillance in the case of radionuclide release (dry storage). Also there is usually no effective multi-barrier system in case of severe impacts, like an airplane crash, for all storage concepts. In most cases there is just one barrier (dry storage in casks), in some cases (wet storage pool in La Hague, France) there is no effective barrier against such effects from outside. A safety comparison leads to the result that dry storage in casks seems to be the kind of storage which is most durable, but the risk of radionuclide release remains. It is possible to increase the existing safety measures, but among other things, economic reasons are against it.

All storage concepts can be realized on the site of the nuclear power plants or away (centralized) from the reactor. To decrease transports and handling of the fuel and therefore to reduce the risks, on-site storage should be chosen. For example, in Germany, this has been realized in recent years (BFS 2005).

About 95 percent of all radioactive wastes are low- or medium-active. These types of waste are stored in containers above ground, mostly in kinds of industrial halls. In case of longer storage periods, the treatment respectively conditioning of the waste is necessary for safety and economic reasons, i.e., for gaseous and liquid waste. This reduces the possible release of radionuclides during regular handling and storage, and in case of incidents and accidents. Also, the volume of waste is reduced by modern conditioning methods; this leads to an increase of storage capacity. However, long-term stability and gas production from reactions between waste, matrix, and package are problems for a part of the waste, for example when using concrete as immobilization matrix.

In case of severe accidents, relatively large releases of radionuclides are possible in spite of the lower activity of the waste. This is true especially for an accidental or intentional airplane crash. Because of the lower radioactive inventory, the realized safety measures are smaller in comparison with the storage of fuel elements or high-active waste.

The storage of low- and medium-level waste can be carried out at the reactor or in central facilities. The first one should be preferred due to less handling and the lower number of transports.

For interim storage of spent fuel, terrorist attacks are to be consider as well for nuclear power plants. Reactors may be a major target indeed but the hazardous potential of big storage pools (in Europe par example at reprocessing plants) is comparable, and spent fuel in casks are a negative symbol for the nuclear industry in some countries, like Germany. In addition, there is often easier access to storage facilities and perhaps fewer security measures. Therefore interim storage may be a target for terrorists.

Final disposal

What has to be disposed of?

Energy production in nuclear power plants—as well as specific applications in some fields of research, medicine, and industry—are entailed with the generation of radioactive wastes. The ionizing radiation released from these wastes may cause genetic modifications and cancer diseases and, thus, poses a danger to humans and the environment. Therefore, radioactive wastes have to be isolated from nature and safely managed. The kind of waste management and the concrete requirements of their handling are determined by the risk potentials of the different wastes. This potential is mainly caused by the nature and intensity of the ionizing radiation emerging from the radionuclides in the waste and the resulting radiotoxicity respectively, as well as the length of the time span for which the waste poses a hazard to humans and the environment. Additional factors are those waste properties determining the handling and disposing of the waste, particularly the heat generation caused by the radioactive decay of radioactive isotopes.

In detail, the spectrum of radioactive wastes arising in different countries, and their differentiation with respect to their management, depends not least on the question of whether the nuclear energy program includes the reprocessing of spent fuel (see chapter 12), as, for example, in France, or whether spent fuel is disposed of directly. Countries which do not reprocess spent fuel are treating it de facto and legally as waste.

The time span during which the waste poses a radiological threat to humans and the environment depends on the half-life of the radionuclides in the waste. Radionuclides with half-lives of ≤30 years are customarily designated as short-lived. Radionuclides with longer half-lives are found particularly in high-level radioactive wastes and to some extent in intermediate-level wastes. The major proportion of these wastes comes from nuclear energy production. One of those radionuclides of particularly long half-life is uranium-235 (half-life: 704 million years). During nuclear energy production, a broad range of radioisotopes of very different half-lives is developed, including, for example, plutonium-239 (half-life: 24,110 years), caesium (half-life: 30.2 years), cobalt-60 (half-life: 5.3 days), which are to be found in different categories of waste.

Heat generation by decay of radionuclides is mainly restricted to highly radioactive wastes from nuclear energy production. For most of the quantitatively dominating radioisotopes, it declines relatively fast, facilitating the waste management after some decades already. For the final disposal of the waste, however, the ongoing heat production may cause long-term problems due to the potential influence on the host rock properties that have to be evaluated carefully.

Despite the fact that protective goals and safety principles for radioactive waste management are similar in most of the countries producing nuclear energy (see chapter 3), there are clear differences with regard to the waste management paths chosen for different wastes types. The reasons are based on, for example, economic considerations or organizational requirements emerging from the scale of the national atomic program and the answer to the question “reprocessing of spent fuel - yes or no?”

Internationally, the most important criteria for the assignment of radioactive waste to a specific waste management path are the kind, the intensity of radiation, and the half-life of the dominating radioisotopes. Regarding the intensity of radiation, the waste is differentiated as follows:

- low-level radioactive waste
- intermediate-level radioactive waste
- high-level radioactive waste

With regard to the waste management path, low-level and intermediate-level wastes containing primarily short-lived radioisotopes (half-lives: $\leq$30 years) and wastes containing larger amounts of long-lived radioisotopes (half-lives: $\geq$30 years) respectively are normally grouped to individual waste categories. High-level active radioisotopes with dominantly short half-lives mainly result from nuclear weapon production. These wastes play a role only in countries with such programs. In the United States, a repository for this type of waste was opened in a deep-lying rock-salt body in 1999 near Carlsbad, New Mexico. Wastes arising from nuclear energy generation normally contain larger amounts of long-lived radioisotopes, usually disposed of together with long-lived intermediate-level radioactive wastes. However, due to different heat generation, there is the need for differentiation between these waste categories.

Depending on the specific properties of wastes and resulting safety requirements, the different categories of waste are assigned to different waste management paths. For short-lived low- and intermediate-level waste, in practice, final disposal on the surface, for example in France and the United States, or near to the surface, for example in Sweden and Finland, are the preferred ways of management (see chapter 5). All long-lived and high-radioactive wastes are intended to be disposed of in deep geological formations.

In contrast to this international practice, after the pre-determination of the repository sites of Gorleben and Konrad, the radioactive wastes in Germany are differentiated according to their heat production, while the half-life of the contained radionuclides is of minor relevance. In contrast to some other countries (e.g., France), it is allowed in Germany to exempt wastes of very low radiation for disposal in household waste dumps or even for use as an economic good, if the measured radiation is below the clearance levels as defined in the Radiation Protection Ordinance (STRLSCHVO 2001). Elsewhere (e.g., in France) radioactive wastes of similarly low intensity of radiation are disposed of in surface repositories specifically designed for this type of waste.

Actual situation

The technical-scientific discussion about radioactive waste management is as old as the production of these wastes through military and civil use of nuclear energy. Already during the fifties and sixties of the last century, a broad range of waste management options was discussed. Besides final disposal being still followed today, or at least intended, this range comprised also rather exotic options, like disposal in space or in Antarctic ice masses. In the fore of this discussion about options were the long-lived intermediate-level wastes and, particularly, the high-level radioactive heat generating wastes (including spent fuel). During the sixties of the last century, the final disposal of these wastes in deep geological formations of the continental earth's crust became widely accepted. Which geological formation was or is preferred in the different countries depends on the geological situation and the relevant political and societal conditions. Decisive for the final disposal option were safety-relevant as well as economic arguments.

In contrast, the waste management of low-level and intermediate-level wastes was seen as less problematic. Relatively early, the dumping of such wastes in the sea and/or—in several countries—the final disposal on the surface or in shallow depths of the continental earth's crust was practiced. Based on the London Agreement for the protection of the sea and its later modifications, waste dumping in the sea was banned in 1993. Today, in several countries, repositories for (short-lived) low-level and intermediate-level wastes are already in operation or planned. In Germany also the final disposal of these wastes in deep geological formations is planned. For the former iron ore mine Konrad, in the city of Salzgitter, a corresponding license was granted in 2000.

Final disposal means the concentration of the radioactive wastes in a facility designed and constructed for this purpose with the aim to isolate the wastes from humans and the environment. Normally, final disposal is applied without the intention of retrieving waste. Depending on the type of waste and resulting time spans of hazard, the repositories may be placed on the surface—normally as mines—or in more or less deep formations of the earth's continental crust. On-surface disposal is restricted to short-lived low-level and intermediate-level wastes only. Corresponding repositories are constructions isolating the wastes from humans and the environment by means of technical barriers. These barriers require monitoring and maintenance. For repositories in deep geological formations, the long-term protection of humans and the environment is predominantly provided by the passive and, thus, maintenance-free geological barriers (see chapter 4).

So far, a repository for long-lived, particularly high-level radioactive wastes does not exist, although during the seventies and even the sixties of the last century, several countries took concrete steps toward final disposal. However, almost all countries have been or are even still facing retardation of their waste management programs. The main reason is the underestimation of the technical-scientific and societal problems related to the realization of such plans. Societal resistance in particular caused a revival of the discussion about management of radioactive wastes and about new siting processes including societal aspects (see chapter 9). Relatively far advanced are the repository plans and even their realization, for example in the United States (Yucca Mountain) and in Finland (Olkiluoto).

Safety principles, safety requirements

On an international level, these are the main safety goals of radioactive waste disposal:

- Final disposal has to ensure that humans and the environment are appropriately protected against radiological and other dangers.
- The potential effects of the final disposal on humans and the environment should not exceed the extent of effects accepted today.
- Future generations should not be saddled with inappropriate burdens.
- The potential effects of final disposal on humans and the environment outside the borders of a country must not exceed the effects allowed within the country.

In many countries, including all countries of the European Union, these requirements were passed into law and form an essential basis for the formulation of (or the confirmation of existing) concrete national requirements on final disposal. This includes radiological standards being met through to the final disposal of radioactive wastes, as well as exceeding requirements, for example, the principle of minimization of effects being part of the legislation in several countries, including Germany's Radiation Protection Ordinance.

Standards for the assessment of the long-term safety of closed repositories are referring to the highest accepted doses through radiation exposure to humans or the related risk respectively to suffer from a cancer disease. Valid standards of different countries for the maximum permissible effective dose are in the range of 0.1 to 0.3 mSv per year. Normally, standards referring to risk are in the range of 10^{-4} to 10^{-6}, meaning that only one person out of 10,000 or 1 million respectively being exposed for their entire life to the maximum permissible dose may get cancer.

Standards can finally be applied to repositories only after the site of concern has been investigated comprehensively. The consistent application of the requirement to minimize the effects of exposure at that time is only possible for the final design and the construction of the repository. However, the principle of minimization demands:

- avoiding every unnecessary exposure to radiation or contamination of human beings and the environment;
- keeping it as low as possible with regard to the status of science and technique and considering the individual case—even if dosage or contamination are below the standards.

In addition to the radiological preconditions, specific requirements for the protection of environmental media may have to be considered or even to be met for final disposal. In Germany, particularly, the so-called principle of concern according to the Water Act has to be considered. This principle demands strong protection of water in the case of final disposal of radioactive waste, particularly groundwater, against harmful contamination or any other detrimental change of its properties and includes not only the radioactive content of wastes but accompanying non-radioactive substances as well.

For the consistent realization of the mentioned radiological goals, the International Commission of Radiological Protection suggests the optimization of radiation protection during all phases of repository design (ICRP 1998). This expressly includes the site selection and requires the application of a qualified selection procedure based on a step-wise safety concept (multi-barrier system) and on the selection of a robust repository site. Following similar ideas and including the requirements of groundwater protection (see above), the German Federal Office for Radiation Protection (BFS) has developed its (not yet published) “Principles for Safe Final Disposal” (BFS 2004).

In the proposal of the German Committee on Site Selection Procedure (AKEND) for a new siting procedure, these radiological and non-radiological requirements are reflected by emphasizing the particular contribution of the geological barriers to the long-term safety and in the following protective goal requirements on a repository site:

- For the case of the normal evolution of the repository site of concern, no release of harmful substances from the isolating rock zone during the isolation period of the order of one million years. Additionally, safety reserves have to be shown with respect to the isolation of harmful substances.
- For the case of extraordinary developments, the standards valid for humans and the environment have to be met.

Altogether, these requirements result in the search for the “best possible” repository site—meaning that site which turns out to be the best according to the rules of the siting process and the state of scientific and technical knowledge and which will in all probability meet the basic requirements and other safety-related requirements (see chapter 9).

Why repositories in deep geological formations?

In addition to the general requirements on final disposal, the specific aim of the final disposal of radioactive wastes in deep geological formations is the isolation of the waste from humans and the environment for very long (“geological”) periods of time. Worldwide, it is pursued with special regard to high-level and long-lived intermediate-level radioactive wastes. Today, final disposal in a mine solely constructed for this purpose is intended.

In contrast, short-lived low-level and intermediate-level radioactive wastes in most countries are intended to be disposed of (or are already disposed of) at shallower depths or even on the surface. By contrast, it was already decided upon in Germany very early (2. Atomic Program 1963–1967) to dispose of all kinds of radioactive wastes in deep geological formations. Main reasons were the dense population of Germany and the intensive use of the environmental media soil and water (Schwibach 1967). This alternative type of final disposal has already been practiced in Germany by the so-called test emplacement in an abandoned saltmine (Asse II) near Wolfenbüttel (1967–1978) and the operation of the repository for short-lived low-level and intermediate-level radioactive wastes at Morsleben (1978–1998).

It can be stated that the disposal in deep geological formations after appropriate site selection has decisive advantages in comparison with all other disposal options on earth. The advantages are above all:

- large distance between wastes and biosphere;
- high and long-term efficient retention capacity of the geological barriers against radionuclides (and other harmful substances);
- slowness of geological processes, including metabolism and transport of substances in the geosphere and resulting reliability of time-related statements about the functioning of the repository system;
- passive functioning of the main barriers of the disposal system (geological barriers) without the need for monitoring and repair measures.

In addition, the properties of the geosphere providing these advantages cannot or can only be influenced by human impact to a minor degree. Therefore, the long-term safety of a closed repository does not depend on the awareness and the technical and economic potentials of future generations. These can, anyway, only be predicted with greater difficulties than the evolution of the geological barriers of a disposal system (Buser 1997; Gruppe Ökologie 2001; AKEND 2002). Additionally, human intrusion into a sealed repository in deep geological formations in case of war or by terrorism is highly improbable.

It is obvious that these advantages hold for all kinds of radioactive wastes, but they are not regarded as necessary for short-lived wastes by all countries and institutions and are not accordingly used. However, these advantages are effective only if the repository site was selected with emphasis on safety-related aspects and if its suitability is credibly demonstrated by the evidence of long-term safety (see chapter 9).

Final disposal - necessary with and without ongoing use of atomic energy?

Radioactive wastes of different origin already exist in all countries with nuclear energy programs or other applications of nuclear engineering. These wastes, by no means, will not vanish as a result of phasing out nuclear energy production. Their safe management will remain indispensable.

The worldwide delays in the allocation of repositories, particularly for high-level and long-lived intermediate-level radioactive wastes, are indicators that waste management is a technical-scientific and a societal problem at the same time. This problem will certainly grow with any increase in the amount of wastes. In contrast, the phasing out of nuclear energy production will facilitate the national solution of the waste management problem: On the one hand, the amount of wastes to be disposed of and their allocation to the different waste categories are at least extensively determined, easing site selection and repository design; on the other hand, the willingness of affected people to accept a repository for those wastes that have to be indispensably disposed of will possibly increase. In contrast, the unlimited operation of nuclear power plants would significantly increase the volumetrical requirements on a repository or even result in the demand for several repositories.

Which problems with final disposal?

During final disposal of radioactive wastes in facilities on the surface or near the surface, the advantages of final disposal in deep geological formations mentioned in chapter 4 are not effective (Gruppe Ökologie 2001): The wastes are placed directly within the biosphere and the risk of regarding such a repository as a passive barrier system and leaving it to itself is much too high. The passive contribution of geological barriers to the protection of humans and the environment is significantly smaller when compared to larger depths. Therefore, technical barriers and measures for monitoring and, if necessary, repair are indispensable. Accessibility of the wastes and sensitivity to terrorist dangers are additional disadvantages and necessitate the protection of the facility against unwanted interference. Albeit repositories on the surface or near to it are reserved for short-lived low-level and intermediate-level radioactive wastes, they need institutional surveillance for several centuries to ensure the protection of humans and the environment. Reliable predictions about the existence and stability, respectively, of the institutions essential for this purpose and, accordingly, the bearing society are only conditionally possible. Looking closer, final disposal on the surface or near to it turns out to be an economically convenient waste management solution for today but also a hygienic risk and a possible economic burden for future generations.

Although final disposal of radioactive wastes in deep geological formations of the continental earth’s crust is regarded and pursued today as the safest long-term management option by the national and international institutions which are responsible for radioactive waste, it is not without disadvantages. By all means, there were and there are reservations against this variant of final disposal outside the responsible institutions. They are resulting mainly from:

- the discrepancy between the long time span during which the radioactive wastes pose a threat to humans and the environment and the—with the length of the period of concern—decreasing significance of the needed predictions about the functioning of the barriers of a repository;
- the missing chance to observe the behavior of the barrier system after closure of the repository and reestablishment of the long-term status of the system;
- the missing chance to intervene after misinterpretation of the functioning of individual barriers and their failure respectively;
- the missing reversibility of final disposal (retrievability of wastes) after closure of the repository.

These concerns exist and rightly so; they have to be and can be encountered by careful site selection and diligent evidence of long-term safety when considering all relevant aspects. Moreover, it must not be ignored that waste management options providing the chance to intervene into the repository system and to reverse the disposal (to retrieve the wastes, see chapter 8) may include considerable disadvantages with regard to long-term safety.

The final disposal of certain radioactive wastes in host rocks of high-retention capacity against radionuclides due to low permeability faces the specific problem that gas generation from wastes may impair the functioning of the geological barrier. On the one hand, resulting increased gas pressures in the closed repository may cause the formation of cracks in the host rock, while on the other hand a change of the chemical milieu in the near-field of the emplacement areas may facilitate or accelerate the transport of radionuclides. Gas production to a larger extent is mainly restricted to low-level and intermediate-level wastes. According to actual estimates, the impacts do not mean an exclusive argument against final disposal in deep geological formations, but they need to be carefully addressed in the evidence of long-term safety and in the design of the repository, if necessary.

Evidence of long-term safety, isolation, and evidence period

All host rocks and all repository sites envisaged for the final disposal of radioactive wastes exhibit safety-related advantages and disadvantages. This results in extensive methodological requirements for the proof of suitability of the site which is finally selected. This applies also to the final disposal in deep geological formations, albeit it shows safety-related advantages as compared to the other waste management options currently under discussion. The evidence of long-term safety for a certain repository site is opposed by the above mentioned disadvantages (see chapter 6). They arise particularly from the long time periods that have to be considered and from the inaccessibility of the wastes in the closed repository.

From the half-lives of the radionuclides in the wastes (see chapter 1) follows that, in case of release of radionuclides from the repository, some waste categories pose hazards to humans and the environment for very long time spans. As a consequence, the safe isolation of the waste for a very long time is essential. On a scientific scale, reliable predictions about the behavior of the repository system, particularly its geological barriers, are not possible for the whole period during which certain waste categories have a significantly hazardous potential and for which they consequently have to be isolated from the biosphere. The long-term functioning of the geological barriers depends, not least, on the future geological and climatical processes affecting them. Some of these processes defy reliable long-term prediction, but form a relevant basis for statements on the long-term safety of the repository.

Therefore, it is obviously inadequate to claim the scientific evidence for the isolation of the wastes for the whole time span during which a hazard to humans and the environment may emanate from the wastes. AKEND (AKEND 2002) postulates that reliable predictions about the function of the essential geological barriers of a repository system can be made for a period of the order of one million years and that the evidence of long-term safety can be conducted for this time span. In other countries, the requirements on the length of the time span to be considered for the evidence of long-term safety are somewhat similar, but significantly lower (10,000 years). However, despite the decreased reliability of predictions with the increase of the time span being considered, the assessment of the time spans exceeding the mandatory period must not be renounced.

The mentioned predictive uncertainties may be intensified by deficiencies in the information about the respective repository site as well as the interactions between wastes, technical/geotechnical barriers, and geological barriers used for the prediction; as long as the wastes and the other barriers are accessible for observation, the processes most relevant for the long-term behavior cannot be observed because the repository system has not yet reached its definitive long-term state. However, when this state has been reached, long after repository closure, the repository will no longer be accessible and possible interactions cannot be observed.

According to AKEND (AKEND 2002), it can be concluded from this that the essential fundamentals of the evidence of long-term safety are already formed during the identification of the repository site. The same is largely true for the reliability of the needed predictions. Therefore, the predictability of the repository system has to already be under consideration during the site selection process. On the other hand, it has to be ensured that the information required for reliable evidence of long-term safety is really acquired during the site investigation and that arrangements are made to deal with remaining uncertainties in knowledge and database.

Retrievability

Retrievability means the possibility to retrieve waste (particularly spent fuel and high-level waste) from a repository in case of demand according to a plan and without major technical efforts. Retrievability of radioactive waste is an issue discussed internationally and concentrates on the retrieval of spent fuel elements. Retrievability of disposed waste and reversibility of decisions in waste disposal are currently being considered in many radioactive waste programs worldwide (e.g., United States, Sweden, Finland). The arguments for retrievability are mainly safety-related, ethical, and economic (NEA 2001), for example:

- technical safety concerns that are recognized after waste emplacement or changes in acceptable safety standards
- to recover resources from the repository, for example components of the waste itself
- to use alternative waste treatment or disposal techniques that may develop in the future
- to respond to changes in social acceptance and perception of risk
- the freedom to act for future generations

For all internationally discussed plans on retrievability, final disposal is still the ultimate objective. Before disposal can be realized, several phases have to be carried out with step-by-step backfilling of disposal sections, access drifts, and shafts. The access to the waste becomes increasingly difficult with each phase and the technical effort required for the retrieval also increases. After sealing the repository, retrieval will only be possible using mining techniques. There are no uniform concepts regarding the precise proceedings and durations of the different phases. As for the period for which relatively simple technical retrievability is possible, several decades up to several centuries are being discussed internationally.

The process of ensuring the long-term safety of the repository is based on a carefully selected passive and thus maintenance-free safety system. Without the phase of retrievabilty with facilitated access to the waste, the passive safe repository condition is reached as quickly as possible. However, if facilitated retrievability of the waste is considered to be possible, the passive safe condition will be reached considerably later (depending on the phases of retrievability). Until then, active safety measures in the form of monitoring and control are required—the performance of which can hardly be guaranteed with the necessary reliability. Moreover, active safety measures require stable social and economic conditions, which likewise cannot be guaranteed for the long periods of retrievability.

The ethical principles cited for retrievability, in particular the freedom to act for future generations, are not convincing. It is not acceptable to strive for the fulfillment of an ethical principle if this inevitably leads to a loss of safety. The protection of current and future generations in itself represents a fundamental ethical requirement. This protection is of the highest priority, because without safety all other aspects become, to a large degree, insignificant. Even if choices between options are left open for future generations, the primary responsibility to solve the problem of radioactive waste still rests with the present generation. Retrievability should not be an excuse for indefinite delay of repository development decisions and is not a substitute for a well-designed repository. On the other side, a step-wise repository development program may include measures to enhance the retrievability of waste for a certain time. A recent concept allowing for an extended time for monitoring and easier retrievability was proposed in Switzerland for "monitoring long-term geological disposal," which includes test and pilot facilities as well as organizational and institutional measures (EKRA 2000). The project "Entsorgungsnachweis" has investigated the technical feasibility of such a concept (NAGRA 2002) and societal decision-making is taking place in Switzerland on the future application of the concept.

International approaches to the selection of repository sites

In the general objective of the selection of repository sites (i.e., to find sites for the long-term safe disposal of the wastes produced in the respective counties), different approaches are pursued to achieve this objective as regards the details. This results in more or less clear differences in the actual procedure with regard to the site selection. The main causes are:

- different concepts about the classification according to disposal paths and repository sites, respectively
- different political and legal requirements
- different geological conditions in the area of exploration (national territory)
- different requirements for the site to be selected (suitable, relatively best)

In many countries, activities targeted at the identification of repository sites were started in the seventies. At that time, site selection was only regarded as a technical-scientific task. Transparency and traceability of the decision-making process generally played no or only a minor role. Some procedures were so strongly influenced by external interface that it wasn't the predefined procedure, but rather other arguments which were decisive in the selection (e.g., Gorleben, Germany; Yucca Mountain, United States). Thusfar, none of the national selection procedures started in the seventies has led to the commissioning of a repository for high-active waste and spent fuel.

The negative experiences with site selection procedures as well as social developments during recent decades have led to increased public participation in many countries. The site selection is no longer regarded as a mere technical-scientific process, but requires the consideration of certain social prerequisites and democratic legitimation. Internationally, traceability and transparency of the procedure, as well as acceptance of the selection results, are regarded today as important prerequisites for successful site selection procedures. These have to fulfill the following social and methodical minimum requirements:

- laying down the proceedings and criteria before performance of the respective procedure step
- step-by-step approach, clear structure of the procedure with well-defined work and decision steps, as well as a licensing procedure in several steps
- participation of the public and interested or concerned persons and groups in the procedure at an early stage (with binding character)
- systematic inclusion of socio-scientific criteria
- substantiated criteria

However, the national approaches of the individual countries to meet these requirements are still different, since the reasons for differences in the procedures stated above persist.

The lack of public support in the site selection which can be observed in many countries and the low degree of acceptance of the legitimacy of the procedure by the public are possibly due to the fact that the significance and the requirements related to a real public participation are often underestimated, although their necessity in general is no longer disputed. Exceptions are Switzerland and Sweden, as well as Finland to a certain degree. In the decision-making context, it is clear that any significant decisions regarding site selection and long-term management of radioactive waste will be accompanied by a comprehensive public review with the involvement of a diverse range of stakeholders. The public is not willing to commit irreversibly to technical choices of which they have insufficient understanding and control. The key feature of a step-wise decision-making concept is a plan in which site selection is done by steps or stages that are reversible, within the limits of practability (NEA 2004).

As an example of a modern site selection procedure, the recommendations of the German Committee on a Selection Procedure for Repository Sites (AKEND 2002) are presented in table 3. The cornerstones of the procedure include both technical-scientific and socio-scientific criteria, a clear selection procedure in five steps, the evaluation of all regions of Germany against the same criteria, no pre-selection of potentially suitable geological host formations, comprehensive public participation from the very beginning to the very end, and a regional development that the dilemma between the national task and regional interests shall be defused so that waste disposal has place not only as a burden, but also as a chance (NIES 2004).

Table 3. Procedure steps: criteria, assessment, proceeding, and instruments of public participation

Procedure Steps	**Proceeding, Criteria, Assessment**	**Instruments of Citizens' Participation**
Step 1: Identification of areas fulfilling specific minimum requirements	• geoscientific exclusion criteria and minimum requirements	**For the overall procedure (steps 1 – 6):** • establishment of an information platform • control committee verifies adherence to the rule of the procedure •
Step 2: Selection of partial areas with particularly favorable geological conditions	• geoscientific weighing	
Step 3: Identification and selection of site regions for exploration from the surface (minimum three sites) step backwards, if required	• planning-scientific exclusion criteria • socio-economic potential analysis • planning-scientific weighing criteria • specification of programs for exploration from the surface and corresponding assessment criteria • willingness to participate regarding exploration from the surface • geoscientific and mining aspects	**As from step 3:** • citizens' forum as a central element of participation • center of competent experts supports citizens' forum • round table of stakeholder • determination and willingness to participate in steps 3 and 4 by vote • preparation of regional development concepts • local council/councils teks/s final decision • orienting vote of the public and local councils at the end of step 5
Step 4: Determination of sites for underground exploration (minimum two sites) step backwards, if required	• exploration from the surface and assessment • orienting safety assessment • willingness to participate regarding underground exploration program • development of test criteria	
Step 5: Decision on a site step backwards, if required	• underground exploration and its assessment • safety case • comparison of the different sites explored	
Repository site for licensing procedure		*Source:* AKEND (2002)

Disposal alternatives

In addition to the concept of isolation of radioactive waste in deep geological formations, there are several other disposal alternatives which have been discussed in the past and which were and are partly being practiced, as for example:

- Transport into space

  This is a proposal which has mainly been discussed in the United States in the early phases of concept drafting for the removal of long-lived radioactive waste. The idea has the advantage that the radioactive waste will be permanently removed from the human habitat. Due to the costs involved, the concept alternative is only applicable to small quantities of waste (high-radioactive waste). In addition, there is a considerable risk with incalculable consequences if a launch into space were to fail. If an acceptance of this way of disposal could be achieved at all, it would remain limited to only a few countries due to the sophisticated technology.

- Disposal in the Antarctic ice

  A concept for waste isolation is presented by disposal in the Antarctic ice. In large areas, the Antarctica ice shield is 15 million years old and up to 4 km thick. There are no doubts that the situation will not basically change in the foreseeable future. However, there are essential questions to be resolved regarding the geophysical and geochemical properties of the ice masses and their impact on the global climate. Likewise, changes in the applicable international legal provisions and political agreements would be required. There is no country worldwide currently pursuing such a concept.

- Dumping waste at sea

  The dumping of low- and medium-active waste at sea—as was permitted in accordance with clearly specified conditions of the IAEA—has not been practiced since 1983 in accordance with a voluntary moratorium, and was banned in 1993 by the contracted parties to the London Convention. The concept was aimed at the disposal of short-lived waste at sea depths where an exchange between water layers—with the corresponding consequences for potential radionuclide diffusion—only takes place restrictedly due to reduced flow and high water density. Dumping high-active waste at sea with long-term application of the dilution principle has not been taken into consideration seriously by any country thusfar.

- Sub-seabed disposal

  At the beginning of the eighties, some member states of the OECD/NEA analyzed another option for disposal: the disposal of high-active waste in the seabed. The deep-sea seabeds of oceans have favorable properties in large areas and thick sediment layers have a high retention potential. The probability of an accident is relatively low. However, there are no tried and tested technologies available for the opening up of such a repository and the corresponding emplacement of waste. Such an option would require an amendment to the aforementioned London Convention. This option is not being pursued actively worldwide.

- Near-surface disposal

  The near-surface disposal of short-lived low- and medium-active waste represents the state-of-the-art in science and technology today. Many countries are either in the process of developing disposal facilities or have facilities that are currently in operation (e.g., Europe, United States, Japan, South Africa). Here, the isolation of the waste material for the required, relatively short periods of time (in general less than 300 years) is ensured by the selection of a suitable subsurface with a geological barrier and by the construction of technical and geotechnical barriers. In addition, the facilities are being monitored. After clearance measurements, such repositories would be transferred to the status of a normal storage site. Due to the long decay times, such a concept is a priority not applicable to high-level waste and spent fuel.

Alternatives to disposal

The question of whether there are any alternatives to disposal in deep geological formations is often dealt with in the general public. Ethically founded principles, such as resource protection, but also the demand to keep various options for action open for future generations play an important role in this aspect. Against this background, we will evaluate the most widely discussed alternatives internationally. The alternatives are:

- partitioning and transmutation
- long-term interim storage

Partitioning and transmutation

Partitioning and transmutation means the conversion of long-lived and highly toxic radionuclides into less toxic radionuclides that are as short-lived as possible. The difficulties associated with repository siting—especially the extremely long periods of isolation required—have caused some to view the transmutation of long-lived radionuclides into short-lived ones as a potential solution for the radioactive waste disposal problem. The theory is that a transmutation program would transform the problem of long-term isolation into a far less difficult one of storage for several decades or a few hundreds years.

In a transmutation system, first a reprocessing plant is needed to sort out the radionuclides slated for transmutation by separating certain long-lived radionuclides from the others. Afterwards this allows the selective conversion of long-lived radionuclides into short-lived ones when they are irradiated in a reactor (a critical reactor, which is a self-contained transmutation device, or a sub-critical reactor, which needs an outside source of neutrons to sustain a chain reaction).

Even the most elaborate transmutation schemes (in theory) will leave behind substantial amounts of long-lived radionuclides requiring disposal, while generating large new volumes of operating and decommissioning wastes. Transmutation does not eliminate the need for a high-level repository. No transmutation scheme is able to deal with all the radionuclides concerned since many cannot be transmuted for practical purposes. For example, transmutation of Tc-99 and I-129 is not 100 percent effective, even with multiple passes through the reactor. Finally, new long-lived fission products are created from the fission of the actinides, and fissioning of the actinides is not 100 percent effective in eliminating them. This means there are fundamental and substantial limitations to the reduction in long-lived radioactivity that can be achieved even with an elaborate and very expensive transmutation program. All together it is necessary to operate chemical and nuclear facilities in which the risks involved are by all means higher than the long-run risks posed by a repository.

The only economically sensible way to pursue such a waste management path would be to establish a new branch of nuclear industry that would be solely dedicated to the partitioning and transmutation of radionuclides. The costs of the transmutation system will be prohibitively expensive—even in comparison to the billions to be spent on repository programs.

Finally, the separation of radionuclides necessary for transmutation will increase risks by providing easy access to fissile materials. All separation processes, including those labeled “proliferation resistant” result in increased proliferation risk over the once-through fuel cycle (Zerriffi and Makhijani 2000).

But transmutation is not only considered in the context of managing the waste from the current generation of nuclear reactors. Particularly in Europe (especially France) and Japan, most transmutation schemes assume an indefinite continuation of nuclear power, with transmutation as one part of a new nuclear cycle.

The conclusion of the French “Commission Nationale D’Evaluation” with regard to transmutation is that it is a hope depending on machines that do not exist at present, whether they belong to the Generation IV reactor systems or the sub-critical accelerator driven system (CNE 2005). In any case, the remaining amount of radionuclides would have to be disposed of as long-lived radioactive waste. Therefore transmutation does not present a real alternative to a geological repository.

Long-term interim storage

Concerning long-term storage of radioactive waste (e.g., in the Netherlands), safety would have to be guaranteed by long-term social control. This presupposes the continuity of the present scientific and economic capabilities and the ability and willingness of all members of society to carry out the controls and necessary measures. The long-term storage strategy has indeed a number of technical and ethical arguments in its favor. This concept consists of an approach, wherein one generation would pass on to the next generation a world with “equal opportunity,” and so on for the generations coming after, thus preserving options and avoiding the difficulty of predicting the distant future. According to this idea of a “rolling present,” the current generation would have a responsibility to provide to the next succeeding generations the skills, resources, and opportunities to deal with any problem the current generation passes on. However, if the present generation delays the construction of a disposal facility to await advances in technology, or because storage is cheaper, it should not expect future generations to make a different decision. Such an approach in effect would always pass responsibility for real action to future generations and for this reason could be judged unethical.

A most significant deficiency of the long-term storage strategy is related to the presumption of stability of future societies and their continuing ability to carry out the required safety and institutional measures. There is also a natural tendency of society to become accustomed to the existence and proximity of storage facilities and, progressively, to ignore the associated risks. Such risks would actually increase with time in the absence of proper surveillance and maintenance, leading at some indefinite future time to possible health and environmental damage. There are many well-known examples of bad environmental situations inherited from the past which show that this deficiency of waiting strategy should not be underestimated (NEA 1995).

The demand to keep various options for action open for future generations also presupposes the continuity of the present economic and scientific abilities and skills as well as the willingness of society. Should social upheavals occur, such as wars or the like, that involve negative consequences for economic and scientific capabilities, then the fact that certain options have been kept open will have exactly the opposite effect. As a result, future generations will no longer be able to attend to the waste, with the consequence that safety will be jeopardized and the freedom to act restricted. What needs to be recognized as well is that by shifting the final decision to future generations, the polluter-pays principle is also violated.

The deciding argument is that predictions of long-term social development carry considerably larger uncertainties than predictions of the functional efficiency of geological barriers acting as passive systems of a backfilled and sealed repository. For this reason, no realistic solution to the long-term safe disposal of radioactive waste other than the disposal in deep geological formations has been provided. The general advantage is that certain rock formations only show low permeabilities for fluid phases or that they are even water-tight in the technical sense due to their physical and chemical properties and the rock formations. Partly, the properties have remained unchanged over geological periods of time so that they are able to isolate hazardous substances from the biosphere for periods in the order of magnitude of one million years. However, a prerequisite is the identification of suitable rock zones, for example by means of a criteria-based site selection procedure.

Waste management for new reactor generation (Generation IV)

For reactors of the Generation IV, the lobby for nuclear power again promise a fuel cycle which is closed, however not only for uranium and plutonium, but for all transuranic nuclides. So the isolation requirements for final disposal would be reduced for a time of 1,000 years. Two components are essentially necessary for this new dream:

- partitioning of the nuclides in spent fuel in a very pure manner

- transmutation of the selected transuranic nuclides and of further nuclides in reactors

Therefore a so-called symbiotic fuel cycle shall be established with fast-spectrum reactors and new kinds of thermal reactors.

It seems it will remain a dream like the fuel cycle outlined in the sixties of the last century. A gigantic park of reprocessing plants for partitioning has to be developed and built. All the problems with gaseous and liquid release of radio nuclides, with the management of radioactive and/or chemo toxic waste, with safety and possibly severe accidents and also with security and proliferation are orders of magnitudes higher than for the current reprocessing. The development of fast reactors which can work in the thought-of manner of former years have failed due to technical problems thusfar. There is no reason why it should be seen as better in the future. Some billions of euros would be needed for research and development for the partitioning and transmutation projects. Because it is improbable that all long-lived nuclides can be separated and transmuted, there is a big question mark as to whether isolation requirements for final disposal could be reduced to the strived-for time.

In conclusion, for technical, safety, security, proliferation, and financial reasons, it is not probable that the “symbiotic fuel cycle” will ever be in operation.

Literature

References

AKEND (Arbeitskreis Auswahlverfahren Endlagerstandorte) (2002). Site Selection Procedure for Repository Sites – Recommendations of the AkEnd. Final report, December 2002.

BFS (Bundesamt für Strahlenschutz) (2004). Grundsätze für die sichere Endlagerung. Bundesamt für Strahlenschutz. Entwurf, November 2004.

——— (2005). Dezentrale Zwischenlagerung – Bausteine zur Entsorgung radioaktiver Abfälle. Budesamt für Strahlenschutz, Salzgitter.

Bunn, M., et al. (2003). The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel. DE-FG26-99FT4028, Cambridge, Massachusetts, December 2003.

Buser, M. (1997). Which is More Stable: A Rock Formation or a Social Structure? NAGRA Bulletin, no. 30.

CNE (Commission Nationale D`Evaluation relative aux recherches sur la gestion des dechets radioactifs) (2005). Commission Nationale D`Evaluation relative aux recherches sur la gestion des dechets radioactifs. Rapport D`Evaluation, no. 11, Juin 2005.

Diehl, Peter (1995). Uranium Mining in Europe – The Impacts on Man and Environment. *WISE News Communique* 439/440, September, special edition. http://www.antenna.nl/wise/439-440/cont.html.

——— (2004). Re-enrichment of West European Depleted Uranium Tails in Russia. November.
http://www.wise-uranium.org/pdf/reenru.pdf.

EKRA (Expertengruppe Entsorgungskonzepte für radioaktive Abfälle) (2000). Entsorgungskonzepte für radioaktive Abfälle. Schlussbericht vom 31.01.2000. Im Auftrag des Departements für Umwelt, Verkehr, Energie, und Kommunikation.

ESA (Euratom Supply Agency) (2005). Annual Report 2004. http://europa.eu.int/comm/euratom/ar/ar2004.pdf.

Gruppe Ökologie (1998). Analyse der Entsorgungssituation in der Bundesrepublik Deutschland und Ableitung von Handlungsoptionen unter der Prämisse des Ausstiegs aus der Atomenergie. Im Auftrag der Heinrich Böll Stiftung, Hannover, August 1998.

——— (2001). Vergleichende Bewertung von Entsorgungsoptionen für radioaktive Abfälle (Comparative Evaluation of Disposal Options for Radioactive Wastes).

Abschlußbericht. Im Auftrag des Projektträgers des BMBF und BMWi für Wassertechnologie und Entsorgung, Förderkennzeichen 02 E 9350.

——— (2005). Wiederaufarbeitung deutscher Brennelemente im Ausland. Prepared for Robin Wood, Hanover, Juni 2005.

IAEA (International Atomic Energy Agency) (1995). International Atomic Energy Agency: Regulations for the Safe Transport of Radioactive Materials. Report No. TS-R-1.

——— (1997). International Atomic Energy Agency: Joint Convention on the Safety of Spent Fuel Management and of the Safety of Radioactive Waste Management. Vienna.

——— (2001). Analysis of Uranium Supply to 2050. STI/PUB/1104, ISBN 92-0-100401-X, Vienna, May 2001, 103 pp. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1104_scr.pdf.

——— (2003). Safety and Engineering Aspects of Spent Fuel Storage. 1996 edition (as amended 2003), Vienna.

ICRP (International Commission of Radiological Protection) (1998). Radiation Protection Recommendations as Applied in the Disposal of Long-Lived Solid Radioactive Waste. Publication 81. Annals of the ICRP, vol. 28, no. 4.

Large and Associates (2004). Potential Radiological Impact and Consequences Arising from Incidents Involving a Consignment of Plutonium Dioxide under Tansit from Cogema La Hague to Marcoule/Cadarache. Report Ref-No R3108-A6, prepared for Greenpeace International, March 2004.

Marignac, Y., and X. Coeytaux (2003). The Unbearable Risk – Proliferation, Terrorist Threats and the Plutonium Industry. Report prepared for "The Greens/European Free Alliance" in the European Parliament, June 2003.

NAGRA (Nationale Genossenschaft für die Lagerung radioaktiver Abfälle) (2002). Project Opalinus Clay; safety report. Demonstration of Disposal Feasibility for Spent Fuel, Vitrified High-level Waste and Long-lived Intermediate-level Waste. Nagra Technical Report NTB 02-05. Nagra, Wettingen, Switzerland.

NEA (Nuclear Energy Agency) (1995). The Environmental and Ethical Basis of Geological Disposal of Long-Lived Radioactive Wastes. A Collective Opinion of the Radioactive Waste Management Committee of the OECD Nuclear Energy Agency.

——— (2001). Reversibility and Retrievability in Geologic Disposal of Radioactive Waste – Reflections at the International Level.

——— (2004). Stepwise Approach to Decision Making for Long-term Radioactive Waste Management – Experiences, Issues and Guiding Principles. NEA report no. 4429.

——— (2004). Uranium 2003 – Resources, Production and Demand. OECD Nuclear Energy Agency / International Atomic Energy Agency, ISBN 92-64-01673-2, Paris 2004, 302 pp. http://www.oecdbookshop.org/.

NERAC (U.S. DOE Nuclear Energy Research Advisory Committee) (2002). A Technology Roadmap for Generation IV Nuclear Energy Systems. December 2002. http://www.ne.doe.gov/nerac/FinalRoadmapforNERACReview.pdf.

Öko-Institut (2000). Ermittlung der möglichen Strahlenexpositionen der Bevölkerung aufgrund der Emissionen der Wiederaufarbeitungsanlagen in Sellafield und La Hague. Im Auftrag des Bundesamtes für Strahlenschutz, Februar 2000.

Schwibach, J. (1967). Research on the Permanent Disposal of Radioactive Wastes in Salt Formations in the Federal Republic of Germany. In: IAEA (1967), publication STJ/PUB/156, pp. 465-477.

STRLSCHVO (Strahlenschutzverordnung) (2001). Verordnung über den Schutz vor Schäden durch ionisierende Strahlung in der Fassung der Bekanntmachung vom 20. Juli 2001. BGBl I, S. 1714.

WNA (World Nuclear Association) (2005). World Nuclear Association homepage. http://www.world-nuclear.org/.

WUP (WISE Uranium Project) (2005). WISE Uranium Project homepage. http://www.wise-uranium.org/.

Zerriffi, H., and A. Makhijani (2000). Nuclear Alchemy Gamble: An Assessment of Transmutation as a Nuclear Waste Management Strategy. Prepared for the Institute for Energy and Environmental Research, May 2000. http://www.ieer.org/reports/transm/.

Further reading (history of uranium mining)

Amundson, Michael A. 2002. Yellowcake towns – uranium mining communities in the American west. University Press of Colorado. Hardcover edition: ISBN 0-87081-662-4; paperback edition: ISBN 0-87081-765-5.

Ball, Howard. 1993. Cancer factories – America's tragic quest for uranium self-sufficiency. *Contributions in Medical Studies* 37. Connecticut: Greenwood Press. ISBN 0-313-27566-1.

Beleites, Michael. 1992. Altlast Wismut – Ausnahmezustand, Umweltkatastrophe und das Sanierungsproblem im deutschen Uranbergbau. Frankfurt a.M.: Brandes & Apsel Verlag. ISBN 3-86099-104-3. http://www.wise-uranium.org/uwispb.html.

Beleites, Michael. 1988. Pechblende – der Uranbergbau in der DDR und die Folgen. Wittenberg. http://www.wise-uranium.org/uwispb.html.

Eichstaedt, Peter H. 1994. If you poison us: uranium and Native Americans. Santa Fe: Red Crane Books. ISBN 0-878610-40-6.

Karlsch, Rainer, und Harm Schröter (Hg.). 1996. "Strahlende Vergangenheit" – Studien zur Geschichte des Uranbergbaus der Wismut. St. Katharinen: Scripta Mercaturae Verlag. ISBN 3-89590-030-3.

Karlsch, Rainer, und Zbynek Zeman. 2002. Urangeheimnisse. Das Erzgebirge im Brennpunkt der Weltpolitik 1933–1960. Berlin: Ch. Links Verlag. ISBN 3-86153-276-X.

Heinrich Böll Foundation

The Heinrich Böll Foundation, affiliated with the Green Party and headquartered in the Hackesche Höfe in the heart of Berlin, is a legally independent political foundation working in the spirit of intellectual openness.

The Foundation's primary objective is to support political education both within Germany and abroad, thus promoting democratic involvement, sociopolitical activism, and crosscultural understanding.

The Foundation also provides support for art and culture, science and research, and developmental cooperation. Its activities are guided by the fundamental political values of ecology, democracy, solidarity, and non-violence.

By way of its international collaboration with a large number of project partners – currently numbering about 100 projects in almoust 60 countries – the Foundation aims to strengthen ecological and civil activism on a global level, to intensify the exchange of ideas and experiences, and to keep our sensibilities alert for change.

The Heinrich Böll Foundation's collaboration on sociopolitical education programs with its project partners abroad is on a long-term basis. Additional important instruments of international cooperation include visitor programs, which enhance the exchange of experiences and of political networking, as well as basic and advanced training programs for committed activists.

The Heinrich Böll Foundation has about 180 full-time employees as well as approximately 320 supporting members who provide both financial and non-material assistance.

Ralf Fücks and Barbara Unmüßig comprise the current Executive Board. Dr. Birgit Laubach is the CEO of the Foundation.

Two additional bodies of the Foundation's educational work are: the "Green Academy" and the "Feminist Institute".

The Foundation currently maintains foreign and project offices in the USA and the Arab Middle East, in Afghanistan, Bosnia-Herzegovina, Brazil, Cambodia, Croatia, the Czech Republic, El Salvador, Georgia, India, Israel, Kenya, Lebanon, Mexico, Nigeria, Pakistan, Poland, Russia, South Africa, Serbia, Thailand, Turkey, and an EU office in Brussels.

For 2005, the Foundation had almost 36 million € public funds at its disposal.

Heinrich Böll Foundation, Hackesche Höfe, Rosenthaler Str. 40/41, D-10178 Berlin, Germany, Tel.: 030-285 340, Fax: 030-285 31 09, E-mail: info@boell.de, Internet: www.boell.de

NUCLEAR POWER: MYTH AND REALITY – The publication, by the Heinrich Böll Foundation, of six issue papers on nuclear power is a contribution to the debates on the future of nuclear energy. The publication coincides with the 20th anniversary of the Chernobyl disaster. The issue papers give an up-to-date overview of recent developments and debates concerning the use of nuclear power world-wide. Their aim is to provide informed analyses for decision makers, journalists, activists, and the public in general.

Nuclear Issues Paper Series
Editor: Felix Christian Matthes
Nuclear Power: Myth and Reality. By G. Rosenkranz
Nuclear Reactor Hazards. By A. Froggatt
The Nuclear Fuel Cycle. By J. Kreusch, W. Neumann, D. Appel, P. Diehl
Nuclear Energy and Proliferation. By O. Nassauer
The Economics of Nuclear Power. By S. Thomas
Nuclear Energy and Climate Change. By F. Ch. Matthes

Co-published by wise

NUCLEAR ISSUES PAPERS AT THE www.boell.de/nuclear