Section III The Nuclear Waste Issue and the Future

8 Partitioning and Transmutation – An Alternative to Final Disposal. An Issue in Focus

8.1 Introduction

In research circles, the possibility of radically reducing the radiotoxicity of spent nuclear fuel through a method known as partitioning and transmutation (P&T) has already been discussed for several decades. The technology comprises complex scientific and technical issues. How is it possible that also politicians and the public pay so much attention to such an issue?

The Swedish Act on Nuclear Activities requires that anyone who has a licence to conduct nuclear activities should be responsible for ensuring that the necessary measures should be adopted to ensure that nuclear waste generated by the activities is handled and disposed of in a safe manner. The Swedish strategy for the handling of spent nuclear fuel is that the fuel should be directly disposed of. The main work in the area therefore focuses on developing and constructing a geological repository where the spent nuclear fuel can be kept isolated from the biosphere (the environment of human beings and other living creatures) for hundreds of thousands of years, namely, until the hazardous radioactivity has decayed. This is the basis of the Swedish KBS-3 concept.

Early in the disposal development process, it became evident that alternatives would be necessary if the KBS-3 concept, for some reason, could not be realised. In its decision on SKB's research programme, the Government established that development work should be conducted on P&T as a possible alternative solution. Furthermore, the Environmental Code expressly requires alternative methods to be investigated and reported in the environmental impact statement, which is to be attached to an application for permission under the Environmental Code and the Act on Nuclear Activities.

The bodies reviewing SKB's research programme (authorities, municipalities, universities, NGOs etc.) have agreed that SKB must study alternatives to the KBS-3 concept. The reasons given in support of this view are both formal (for example requirements on alternative accounts under the Environmental Code) and general expressions of uncertainty regarding whether it would be possible to realise the KBS-3 method. Although the details and the line of reasoning are different, the conclusion is that SKB must describe alternatives to KBS-3 and that P&T is considered to be an alternative.

In its most perfect form, transmutation may mean that the parts of the fuel that remain radioactive for a very long time are completely eliminated. The technology that is necessary for the application of the method has been developed by researchers within several essential areas. However, major technical problems still have to be resolved and these issues have generated research programmes in the EU, the USA, Russia, Japan, Korea and other nations. National programmes in several European countries were also created. All parts of the technology must also be tested in demonstration plants before operating characteristics, safety issues, operating economy etc. can be evaluated.

If successful, it is expected that P&T will lead to a reduction in the volume and in the radioactivity of the remaining fuel by one hundred times. After treatment, the fuel radioactivity would decay to a non-hazardous level in 500 to 1,000 years. A small part of very long-lived substances (a few tenths of a per cent of the same long-lived substances as in the spent nuclear fuel) must still be deposited in a repository due to the fact that the different substances cannot be completely separated. The repository would be considerably smaller and would not need to function for as extensive a period of time as a conventional, direct disposal repository for spent nuclear fuel.

There are also advocates of P&T among groups and individuals who are opposed to the final disposal of spent nuclear fuel. In some accounts, P&T is presented as a present-day method of completely getting rid of hazardous waste. However, this is not the case.

In the Swedish debate about P&T, the technical and other problems associated with the separation (partitioning) of substances in spent nuclear fuel, have been eclipsed. It is also well known that radioactive releases to the environment can be significant in connection with the type of separation processes required in connection with P&T.

P&T technology assumes that there will be a continued and extensive nuclear programme in Sweden. Estimates of P&T technology made in the USA and the EU show that 20 to 30 years of research will be necessary in order to realise the technology. This means that sustainable, long-term research and development programmes are required.

Section 8.2 provides a description of P&T and the types of plants required to implement the process. Section 8.3 summarises the state-of-the-art concerning P&T and Section 8.4 provides an overview of ongoing and planned international research. Three scenarios are presented in Section 8.5 which illustrate what the technology would mean for Sweden. In Section 8.6, the entire chapter is summarised. Sections 8.5 and 8.6 can be read independently of Sections 8.3 and 8.4. From Section 8.2, the reader can therefore proceed directly to Section 8.5.

8.2 Basic Principles of P&T

Obviously, it would be very valuable if, in some way, spent nuclear fuel could be treated so that the long-lived radioactivity could be rendered harmless. Much would therefore be gained if the radioactive substances with long half-lives – with respect to both fission products and transuranic elements (substances that are heavier than uranium) – could be converted into short-lived or stable isotopes of different elements. This would then radically reduce the quantity of radioactivity which would have to be deposited in a repository as well as the length of the time that the repository would have to isolate the deposited material.

To understand what P&T is about, it is necessary to know what spent nuclear fuel contains.

8.2.1 The Fuel in the Reactor Core

Uranium Fuel

All of the nuclear reactors in Sweden are light water reactors. Three of the units at Ringhals are pressurized water reactors (PWRs) while the other Swedish reactors are boiling water reactors (BWRs)[1].

Uranium, in the form in which it occurs in nature (natural uranium) is not suitable as light water reactor fuel. The concentration of fissile, and thereby energy-generating, uranium-235 in natural uranium is only about 0.7 %. The rest predominately comprises uranium-238, which is not fissionable in a light water reactor.

Swedish reactor fuel is therefore *enriched*. This means that the proportion of uranium-235 in the uranium is increased in an enrichment facility (abroad). The residual product from this process is uranium with a lower concentration than that of natural uranium, also known as depleted uranium.

In Västerås in Sweden, a fabrication plant has existed for a long time which manufactures fuel for Swedish reactors and for some foreign reactors. The fuel is fabricated from enriched uranium purchased from abroad.

[1] After the close down of the two BWRs at Barsebäck, there are still seven BWRs in operation.

Fresh enriched fuel for a light water reactor has a uranium-235 concentration of about three per cent. The fuel stays three to five years in the reactor core, often being moved to different core positions during that time. When about two-thirds of the uranium-235 that was in the fuel when it was first inserted into the core is used up, the fuel can no longer be used. The spent fuel is then removed from the reactor and first transferred to a spent fuel pool at the nuclear power plant and – after a couple of years of radioactive decay – the fuel is taken by the M/S Sigyn ship to the Central Interim Storage Facility for Spent Nuclear Fuel (CLAB), located on the Simpevarp peninsula in Oskarshamn municipality.

MOX Fuel

Plutonium-enriched fuel can also be used as an alternative to enriched uranium. Fissile plutonium-239 is formed in the reactor fuel when neutrons are captured by non-fissile uranium-238. By *reprocessing* spent nuclear fuel, the plutonium can be chemically separated. The plutonium can then be mixed with natural or depleted uranium to produce new reactor fuel, called Mixed Oxide (MOX) fuel. Typically, fresh MOX fuel contains three to four per cent of plutonium-239 and, also in this case, about two-thirds of the fissile material are used up before the fuel is removed from the core. The spent MOX fuel can then once again be reprocessed. However, the concentration of heavy plutonium isotopes (heavier than 239) increases with each reprocessing, which means that the plutonium that is extracted during each reprocessing becomes less and less useful for fresh fuel fabrication.

As far as we know, MOX fuel has not been manufactured in Sweden. However, the method is well developed and, in principle, it would be possible to use the method in Sweden.

Spent Nuclear Fuel

The spent nuclear fuel stored in CLAB predominately comprises uranium fuel from Swedish boiling water reactors and pressurised water reactors. A small quantity of spent MOX fuel is also stored in CLAB.

While the fuel is in the core, a number of chain reactions occur resulting in the formation of radioactive products. The production of radioactive substances in the reactor fuel during reactor operation occurs in two ways – through *fission* and through *neutron capture*.

During the fission of uranium-235, the nucleus divides into two *fission fragments*. The exact way in which the nucleus divides varies and a large number of elements are represented among the *fission products*. Most of these have short half-lives or are stable. However, there are also some radioactive substances with very long lifetimes. All of the atoms of the fission products are naturally *lighter than the uranium atom* that undergoes fission.

During neutron capture, a free neutron is captured, for example, by a uranium-238 nucleus. Uranium-239 is first formed, but this soon decays in a couple of steps into plutonium-239 which has a long half-life (24,000 years). Many other elements that are *heavier than uranium* – transuranic elements – are also formed in the reactor and several of these also have a long half-life.

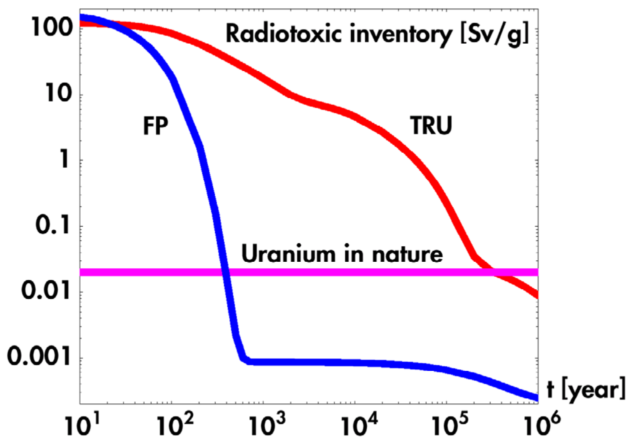

Figure 8.1. Radioactive decay of spent nuclear fuel over time, showing contributions from transuranic elements (TRU) and fission products (FP). The radiotoxicity is compared with that of uranium ore which is present in nature.

About 95 % of the spent nuclear fuel comprises unaffected uranium, while 1.2 % comprises transuranic elements and 4.2 % are fission products.

The largest share of transuranic elements in the waste comprises plutonium (87 %). Besides the fact that plutonium is *radiotoxic*, it can also be used to make nuclear weapons. However, the composition of the plutonium formed in light water reactor fuel (*reactor plutonium*) is not suitable for weapons manufacturing. Nevertheless, after separation from the other substances in the spent nuclear fuel, the material can still be used to make primitive nuclear explosives which, if they fall into the hands of a terrorist organisation, could represent a real threat in a blackmail situation. It should also be mentioned that the reactor plutonium which is contained in the spent nuclear fuel deposited in a geological repository will gradually become a better weapons-grade material over a period of 1,000 years since the plutonium-239 becomes enriched as a result of shorter lifetimes for several of the other plutonium isotopes.

8.2.2 The Basic Principle of P&T

The purpose of P&T is to render the radioactive substances less hazardous in the sense that they are converted (transmuted) into more harmless radioactive products that are radioactive for a short period of time or are completely stable. This can be achieved by irradiating the radioactive substances in the spent nuclear fuel so that these substances (the nuclei of the elements) are converted into other elements (nuclei) with the desired properties. This transmutation is achieved through nuclear reactions between the atoms of the radioactive elements and the particles with which they are irradiated. The radiation, which it is intended to use for the P&T of radioactive substances, is the same as that in our reactors, namely, neutron radiation. However, in order to achieve the desired effect, the intensity and energy distribution of the radiation may need to be different in a transmutation facility than in a conventional nuclear power reactor.

The neutron irradiation mainly causes two types of nuclear reactions, fission and neutron capture, namely, the same type of reactions that occur in uranium-235 and uranium-238 during reactor fuel burning. To render the transuranic elements harmless, irradiation conditions must be created that cause the elements to mainly undergo fission and to form fission products. Energy, which can be used, is also generated during this process. The long-lived fission products, those that are already present in the spent nuclear fuel and the new products that arise from burning transuranic elements, are then transmuted by adding a neutron to the fission product nuclei during irradiation (neutron capture). This nuclear reaction gives rise to elements with other properties, often with shorter half-lives than the original (long-lived) fission products.

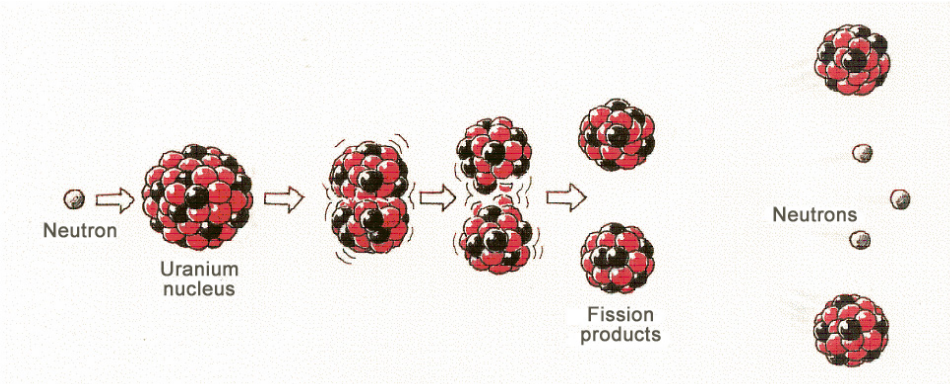

Figure 8.2. An illustration of the fission process. A neutron is captured by a uranium nucleus which becomes excited and undergoes fission, splitting into two fission products and emitting neutrons.

8.2.3 Thermal or Fast Neutrons

The probability of the desired nuclear reactions occurring depends on the energy of the neutrons used to irradiate a certain element. Two types of irradiation occur where the neutrons have different energy distributions (or velocity distributions), namely thermal and fast neutrons. With thermal neutrons, the energy of the neutrons is in equilibrium with the energy of the surrounding atoms in motion. Fast neutrons have a much higher velocity than the thermal energy of the surrounding atoms.

In general, in the case of transuranic elements, the ratio between the probability of nuclear fission and neutron capture (neutron absorption) is greatest in the case of fast neutrons. This means that if the aim is to split transuranic elements, they must be irradiated with fast neutrons.

On the other hand, the probability of a neutron being captured by a fission product is much greater in a thermal neutron flux than in a fast neutron flux. In certain P&T techniques, the fact that the neutron capture process is highly likely to occur for some energies (resonance energies) in a relatively narrow energy range above the thermal energy range has also been exploited.

8.2.4 Partitioning

If P&T is to lead to a substantial reduction of the radiotoxicity of the radioactive waste (a reduction of one hundredfold or more), the spent nuclear fuel must be irradiated in several cycles with an intermediate separation of the elements in the fuel. Material that has been transmuted must be removed so that it does not become radioactive again through further irradiation. Non-transmuted material must be added to fresh fuel for the P&T facility. The elements to be separated depend on the transmutation method that is to be used.

Two different partitioning methods are being studied. In both cases, the aim is to achieve a maximum separation efficiency in order to thereby reduce the quantity of waste to be deposited in a geological repository. A separation efficiency of 99.9 % has been reached for uranium and plutonium, while for other transuranic elements and fission products, the efficiency is between 98 % and 99.9 %.

One method is a refinement of an existing method based on hydrochemical processes (or aqueous processes) and which is used at the existing reprocessing plants, for example in France (La Hague) and Great Britain (Sellafield). At these facilities, plutonium is extracted from spent nuclear fuel by dissolving the fuel in a strong acid. Subsequently, the various components of the fuel are chemically separated for the fabrication of new nuclear fuel (MOX fuel) for commercial thermal nuclear reactors.

The first stage is a refinement of the process used for plutonium extraction (PUREX) where uranium, neptunium and the long-lived fission products, iodine and technetium, are also separated from the other transuranic elements and fission products. Processes are being developed to separate, in subsequent stages, the remaining transuranic elements, americium and curium which, together with neptunium, are called minor actinides (MA) from the remaining fission products. The problem of this separation method is that certain essential chemicals in the separation processes are neutralised when they are exposed to strong ionising radiation. Therefore the radioactivity in the fuel must be allowed to decay during a relatively long period of time before separation can be conducted. All types of processing and separation processes entail increased risk of occupational exposure to radiation and radioactive releases to the environment.

The Swedish Inquiry into Radioactive Waste ("AKA-utredningen") proposed, in the early 1970s, that a Swedish reprocessing plant based on hydrochemical processes should be constructed on the Swedish west coast, north of Gothenburg. These plans were never realised. Instead, the nuclear industry decided to sign a contract with foreign reprocessing facilities (La Hague in France and Sellafield in Great Britain). These contracts have since ceased to apply, since they were no longer meaningful when the decision was made to phase out nuclear power in Sweden and to directly dispose of spent nuclear fuel as waste. An important point of reprocessing is that the plutonium formed in the reactor fuel should be recovered and used for the fabrication of fresh reactor fuel as a step in the efficient management of uranium as a natural resource and in order to prevent plutonium from going astray and being used for the manufacturing of nuclear weapons.

Technology for constructing a Swedish reprocessing plant based on hydrochemical technology is available abroad. However, experience from abroad shows that very large plants are necessary in order for the operation to be cost-efficient. The reprocessing plants that currently exist abroad serve nuclear power customers in several different countries.

As was already mentioned, certain essential chemicals in the fluid separation process become inert when exposed to strong radiation. Therefore, research and development are underway in several countries to develop an alternative partitioning method. This method is based on *pyrochemical processes* which can also work in high radiation fields and, thereby, deal with irradiated fuel from P&T plants. With the pyrochemical method, which entails a more compact P&T plant, differences are exploited in the electrochemical properties of different elements in the high-level part of the radioactive fuel which, during electrolysis, is dissolved in molten salts, comprising fluorides or chlorides at a high temperature. During electrolysis, the molten salts which contain the radioactive spent fuel, are placed in a container with two electrodes. Partitioning is achieved by letting the elements in the spent fuel precipitate on one electrode with different electrical voltages between the electrodes.

8.2.5 Technical Alternatives

What would a P&T plant look like? The different solutions which are currently being studied comprise the use of ion accelerators, critical and sub-critical reactors as well as thermal and fast reactors of different designs. A critical reactor is a reactor where the neutron production in the fuel exactly balances the neutron losses through reactions in fuel, coolant, construction material and from leakage, while a sub-critical reactor has neutron losses that exceed production. A thermal reactor has a thermal neutron flux in the core, which means that the neutron velocity is in equilibrium with the surrounding atoms in the reactor core, while a fast reactor has a fast neutron flux, namely, neutrons with an essentially higher velocity (energy) than the surrounding atoms. Practically all nuclear reactors that are in operation the world over, including Sweden's light water reactors, are critical thermal reactors. A few fast critical reactors are in operation while other variations of fast reactors are still at the prototype or project stage.

The performance of a P&T plant is not only determined by the intensity and energy distribution of the neutrons in the core, as has been previously mentioned, but also by the neutron economy, namely how many neutrons are available for the transmutation of the waste. It can generally be said that fast critical reactors have a better neutron economy for P&T than thermal reactors. A type of P&T plant which consists of a combination of a powerful ion accelerator and a sub-critical reactor, known as an Accelerator-Driven System, has the best neutron economy.

Accelerator-Driven Systems (ADS) with Fast Sub-critical Reactors

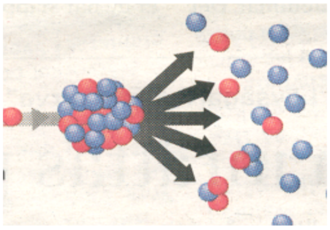

Figure 8.3. *Illustration of the spallation process. When protons (in red) from the accelerator collide at high speed with lead and bismuth nuclei in the centre of the sub-critical reactor, the nucleus splits into several fragments, releasing a large number of neutrons (in blue).*

The Accelerator-Driven System has attracted the greatest interest in the research sphere. A powerful ion accelerator delivers its ion beam (protons i.e. hydrogen atom nuclei) to a sub-critical reactor. The protons bombard a body made of heavy material (for example, a mixture of lead and bismuth in molten form), which is at the centre of the reactor core. When very high-energy (velocity) protons hit atoms of a heavy material such as lead or bismuth, they split into several fragments, releasing a large number of neutrons. The process is called spallation. During each spallation, a few dozen neutrons are released. An intensive radiation field of neutrons is created through the interaction with the fuel which comprises the long-lived transuranic elements from the spent fuel. As a result of its sub-criticality, the reactor will be automatically switched off as soon as the accelerator beam is shut off. This means that the inherent safety for preventing criticality accidents is very high.

As mentioned above, in order to efficiently burn *transuranic elements*, and especially heavy transuranic elements (MAs), a reactor with fast neutrons is required. To avoid fast neutrons from being slowed down (thermalised), a medium with heavy atoms is required. The use of liquid lead/bismuth as a coolant, experience of which has been gained from Russian submarine reactors, has attracted the greatest interest. A sub-critical reactor has safety-related advantages compared with a critical reactor. The reason is that the addition of a large quantity of MAs (minor actinides) at the expense of uranium-238 in the fuel results in a lower level of safety to prevent criticality accidents since the nuclear physics properties of uranium-238 contribute to preventing criticality accidents in a critical reactor.

As has been indicated above, thermal neutrons are required to efficiently transmute long-lived fission products. For this reason, the aim has been to achieve a zone of thermal neutrons on the periphery of the fast sub-critical reactor core, where the transmutation of the fission products can occur. Alternatively, the possibility has been studied of using the resonances in the neutron capture process (transmutation process for fission products) which occurs in a narrow energy field above the thermal zone and which the neutrons pass through as they are gradually slowed down through recurring collisions with heavy atomic nuclei in the coolant (lead/bismuth).

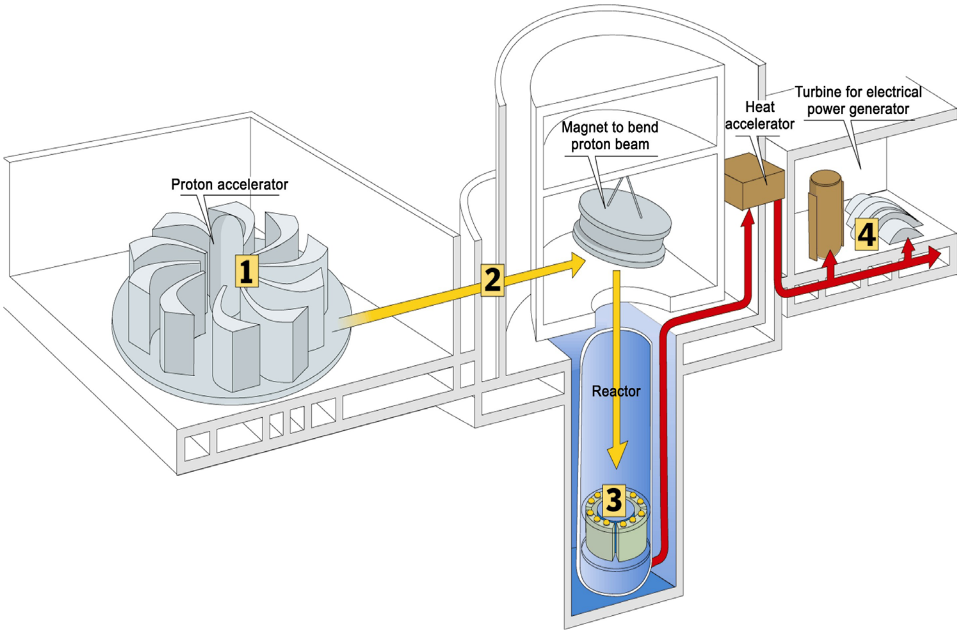

Figure 8.4. *Illustration of an Accelerator-Driven Transmutation System (ADS).*

1. An intense proton beam is generated and accelerated to high energy by a proton accelerator.
2. The high energy protons from the accelerator hit a target of molten lead and bismuth in the centre of a sub-critical reactor. A high neutron flux is generated by spallation reactions.
3. The radioactive waste is put in fuel pins of a molten lead/bismuth cooled reactor. The radioactive species of the waste are transmuted to new species with shorter half-lives by neutron-induced reactions.
4. The heat generated in the reactor can be converted to electrical power in the same way as in ordinary nuclear power reactors.

Accelerator-Driven System (ADS) with a Thermal Sub-critical Reactor

Accelerator-driven systems with thermal sub-critical reactors have also been studied. Systems with molten salts (beryllium and lithium fluorides or sodium and zirconium fluorides) as a coolant, in which the radioactive waste to be transmuted is dissolved, have attracted the greatest interest. Operating experience has been gained from a molten salt critical reactor for energy generation. The reactor was constructed and operated for a few years in the 1960's at Oak Ridge National Laboratory in the USA. Calculations have been performed on the reduction of the radioactive substances in the high-level part of the spent fuel during irradiation in an accelerator-driven system with a sub-critical molten salt reactor. The calculations show that a relatively large reduction in the active substances in the fuel has been obtained after one irradiation cycle without separation. If the newly formed short-lived fission products from the fuel in the molten salts are partitioned, a greater reduction of the radioactive elements can be achieved than if no partitioning of these products is conducted. Studies have been conducted on the possibility of carrying out this "cleaning process" in a directly-connected partitioning facility through which the molten salts from the reactor are continuously circulated. However, this method entails several problems which have not yet been resolved.

An essential difference between transmutation in a thermal neutron flux compared with transmutation in a fast neutron flux is that a small portion of very heavy elements are formed by the thermal flux. These relatively long-lived elements remain in the residual products after transmutation and must be disposed of.

Thermal Critical Reactors

The most proven method of disposing of plutonium is to mix it with depleted or natural uranium to form MOX fuel and to use this fuel in, for example, thermal reacors of the type that we now have in Sweden. A corresponding quantity of enriched uranium does not have to be purchased and the uranium that has been extracted to manufacture the original uranium fuel is managed in a better way. However, this process cannot be repeated more than a few times, since the quantity of heavy plutonium isotopes successively increases, and these isotopes cannot be partitioned from the "recoverable" plutonium (plutonium-239) by chemical means, since they are all the same element. In order to continue to burn the residual plutonium, a critical or sub-critical fast reactor is needed.

Besides plutonium, which has been mentioned above, most of the fission products can be transmuted in reactors with a thermal neutron flux. However, the transmutation of fission products consumes neutrons, unlike the burning of plutonium which produces new neutrons. As mentioned above, neutron economy (the number of neutrons available for transmutation processes) is low for thermal critical reactors, namely nuclear reactors of a conventional type. In order not to obtain unreasonably long transmutation times, the better neutron economy is required that is provided by an accelerator-driven system or other critical reactors specially adapted to transmutation.

Fast Critical Reactors

For residual plutonium from MOX burning of plutonium, and for efficient burning of most of the other transuranic elements in spent fuel (the minor actinides, neptunium, americium and curium), fast reactors are required. The neutrons in fast reactors have higher velocities than the thermal kinetic energy of the atoms in the core. The properties for the transmutation of several different types of fast critical reactors have been studied. Even if the neutron economy for transmutation is better for these reactors than for the thermal critical reactors, a substantial park of fast neutron reactors are required in order to achieve a reasonable transmutation capacity. The reason for this is that only a small addition of minor actinides (neptunium, americium and curium) can be achieved in the uranium fuel in order to avoid jeopardising the reactor safety margins.

Prototype fast critical reactors for power generation have previously been constructed abroad. Usually, these reactors are fuelled with plutonium and cooled by liquid sodium. Furthermore, a feature of these reactors is that plutonium can form in a blanket zone of natural or depleted uranium surrounding the core, and the amount can exceed the amount of plutonium burnt up in the reactor core. Such reactors are therefore often called fast breeder reactors. About forty years ago, it was believed that breeder reactors would successively replace today's reactors, particularly because they make efficient use of the Earth's uranium resources. However, in reality, this has not turned out to be the case, at least not so far. The technology is more problematic than for present-day reactors, especially since the reactor is cooled by liquid sodium which is explosive on contact with oxygen.

Since there is a plentiful supply of uranium on the global market as well as a good enrichment capacity, the demand for plutonium for reactor fuel is very low. Instead, plutonium has become something that we would like to get rid of. This is also related to the fact that fuel costs in a nuclear power plant represent a very small portion of the production cost for electricity. It is the high fixed asset costs that affect the price. It could be said that a nuclear power plant is expensive to construct but inexpensive to operate. Therefore, the plant should be operated at full capacity as much as possible. The opposite can be said of an oil-fired plant, for example, which is relatively inexpensive to construct but expensive to operate since oil is expensive as is flue gas cleaning etc.

Furthermore – in the present climate of disarmament – a large quantity of plutonium is becoming available as nuclear weapons are dismantled. This is contributing to making plutonium a surplus good that we would like to render harmless in order to ensure that disarmament is sustainable and so that the plutonium can not be used again for nuclear explosives.

A large-scale expansion of fast critical reactors, where plutonium and minor actinides could be burnt is therefore not probable at present. Instead, accelerator-driven sub-critical systems are used for this purpose, possibly combined with initial plutonium burning, in the form of MOX fuel, in thermal reactors.

Combinations of ADS and Critical Reactors

In order to achieve the best possible incineration of the radioactive portion of spent fuel and also a reasonable economy, combinations of the above-mentioned transmutation methods are also being studied in the national and international programmes. Two main lines can be distinguished depending on whether the irradiation of the radioactive waste is achieved in one step (a single strata), with or without the return of the waste fuel after separation of the fission products, or in two steps (double strata), where plutonium, for example, is burnt in a thermal reactor followed by transmutation of the remaining waste in an accelerator-driven system or in a critical reactor built for this purpose.

The national research programmes focus on transmutation methods that are adapted to each country's nuclear energy programmes so that the two-step principle (double strata) is prioritised in countries where plutonium burning in reactors is already underway (MOX fuel) while research in countries without plutonium burning focuses on the single-step principle. The number of ADS facilities that are required for the incineration of nuclear waste from a group of light water reactors varies depending on the transmutation method. If all transuranic elements are to be burnt in ADS facilities, the need for such facilities is estimated at about 20 % of all of the total number of nuclear reactors, (namely, one ADS facility for each five nuclear reactors). In the two-step alternative, with only burning of MAs in ADS facilities, the need is about 15 % (namely, one ADS facility for each seven nuclear reactors). A description of the research situation in a few prominent countries is provided in Section 8.4.

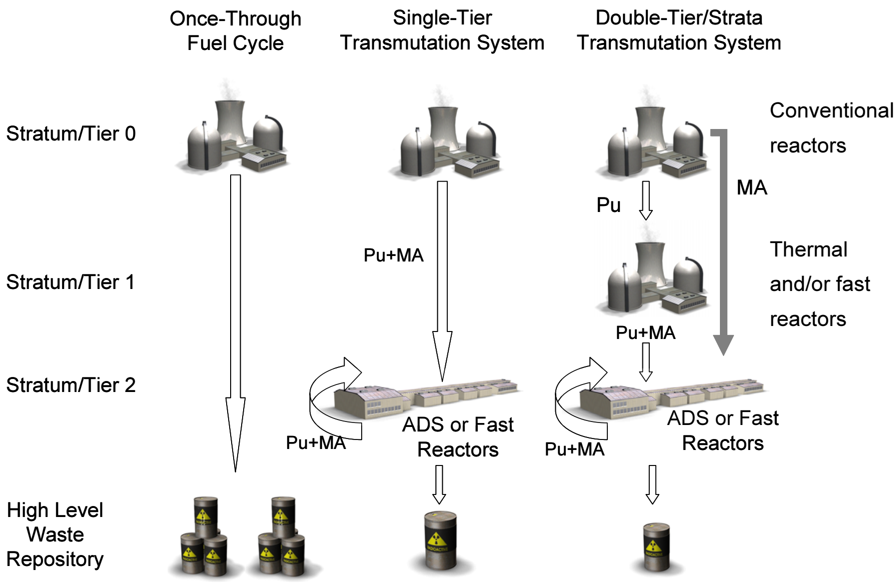

Figure 8.5. Direct or once-through disposal, one-step and two-step transmutation systems (Pu plutonium. MA minor actinides: Neptunium, americium and curium).

8.3 State-of-the-Art

What is our current level of knowledge to apply P&T with the aim of reducing the radiotoxicity and lifetime of spent nuclear fuel?

P&T is based on known principles and scientific facts. The processes (nuclear reactions) in the spent nuclear fuel which lead to the desired results are sufficiently well known so that we can judge the applicability of the method. On the other hand, more detailed knowledge is required to optimise the systems included in a transmutation facility, with respect to operating characteristics, economy etc.

However, the practical application is complex. The level of technical knowledge has developed differently for each of the many parts that make up a P&T plant. This primarily applies to accelerator-driven systems with sub-critical reactors which are intended to be used in practically all concepts for the transmutation of all or parts of the spent nuclear fuel.

The international development of accelerators for high-energy physics in recent decades has represented a technological breakthrough. In itself, this development provided the incentive to start more conscious research in transmutation: This idea existed already during the 1950's and 1960's but was then considered to be technologically difficult to implement. However, the general perception today is that accelerators which meet the requirements for accelerator-driven P&T can be built but with certain reservations with respect to the requirement on sustainable, uninterrupted operation (without short or long outages) for long periods of time.

As described in Section 8.2, the strong ion beam from the accelerator drives an intensive neutron source placed in the centre of a sub-critical reactor. Neutrons which are produced when the ion beam is stopped by a target made of heavy material (usually a mixture of lead and bismuth in molten form) can, with a relatively high accuracy, be calculated for different properties in the ion beam and the target material and design. The technical difficulties are mainly related to the robustness of the window that separates the accelerator from the target. This window is exposed to high radiation doses which result in radiation damage in the material. However, the window is also subjected to thermal forces when the accelerator starts and stops. Another technical problem is the corrosion in the wall material of the container which contains the molten lead/bismuth. The solution to this problem has been taken from the design of Russian submarine reactors which also used molten lead/bismuth as a coolant. A further problem which must be handled is the production of a radioactive polonium isotope which is formed during the irradiation of bismuth and which has a half-life of 138 days. Several projects are underway to solve these problems were the properties of molten lead/bismuth, radiation-resistant material and complete targets with and without windows are being studied.

Programs for calculating operating characteristics, safety aspects, burnup etc. in an accelerator-driven sub-critical reactor are being tested in a number of ongoing experiments. At the same time, methods for continually measuring the criticality (sub-criticality) of the reactor, are being developed. This is important from the standpoint of safety.

Several different coolants are being studied for the sub-critical reactor (molten lead/bismuth, molten sodium or helium gas). Molten lead/bismuth has been judged to be the best coolant in physical and safety terms. The same technological problems with corrosion and polonium production which have been described above for the neutron source placed centrally in the reactor also exist in connection with the reactor design. In addition, there is a problem with the manufacturing of reactor fuel which is to contain plutonium and the minor actinides, neptunium, americium and curium, from the spent nuclear fuel. Several different types of fuel are being studied (nitride, oxide and metallic fuels) where the aim is to achieve a good thermal conductivity, a high melting point and a high radiation acceptance. The latter is required due to extremely high radiation levels in the fuel which can lead to material damage. The mixture of ceramic material in the fuel is being studied in order to reduce radiation damage in the fuel elements.

As described in Section 8.2, an alternative concept is also being studied for the sub-critical reactor, where the spent fuel is dissolved in molten salt, namely fluorides comprising beryllium and lithium or sodium and zirconium fluorides. Knowledge of this type of reactor is based on experience from the operation of a critical molten salt reactor at Oak Ridge National Laboratory, USA, in the 1960's. Even if this type of sub-critical reactor is of interest in principle due to the simpler fuel handling, the technical difficulties are considered to be greater than with the previously described lead/bismuth-cooled reactor. In spite of this, several research projects are underway which are focusing on improving the knowledge of molten salts and their use in reactors.

As was previously mentioned, in order for transmutation to be efficient, a more or less extensive separation of the elements in the spent nuclear fuel is required. In principle, two different methods are being studied. One is based on hydro chemistry and the other on pyrochemistry (see Section 8.2). The first method has been tried and tested and is applied in France (La Hague) and Great Britain (Sellafield) on a commercial basis for the manufacturing of MOX fuel. Research is underway to also be able to partition the other transuranic elements (minor actinides) and certain fission products by similar methods. As was mentioned in Section 8.2, chemicals in the partitioning process are destroyed by high radiation doses. Consequently, the method is not suitable for fresh spent nuclear fuel, especially not recycled transmutation fuel. The radioactivity must decay for several years before partitioning can be conducted using this method which leads to a long treatment time for the spent nuclear fuel, comprising decay, partitioning, fuel manufacturing and transmutation in several cycles. With the second method, which is based on pyrochemistry, high-level material can be treated, but the method is not as developed as the method based on hydrochemical processes. The pyrochemical method has so far been applied with success on a laboratory scale and extensive development work is underway to raise the separation capacity to a commercially interesting level. It is important for the separation process which, as a result of the very high radiation intensity, must take place in radiation-shielded “hot cells”, to also be designed so that radioactive releases are as small as possible.

In parallel with research into the above-mentioned problems in P&T, design studies are underway, partly as a project in the EU’s framework programme, on demonstration facilities for transmutation. Tenders have also been submitted in a few cases for full-scale accelerator-driven transmutation facilities where Prof. C. Rubbia (Nobel prize winner and former head of CERN) is behind a concept involving liquid lead/bismuth as a coolant and Dr C. Bowman (former head of P&T research at Los Alamos National Laboratory, USA, now with his own company in the P&T area (ADNA)) is behind another concept involving molten salts as a coolant. None of the concepts is considered feasible with the current level of knowledge. Initially they will require extensive technical development work.

In summary, it can be said with respect to the state-of-the-art concerning P&T that several technical problems must be solved before a definitive evaluation of the applicability of P&T can be made in technical, safety, economic terms etc. This problem particularly concerns the manufacturing of fuel elements and partitioning of the high-level transmutation fuel. Work is in progress to solve these problems, as has already been mentioned and will be described in greater detail in Section 8.4. So far, the ongoing research has not led to any results that contradict the idea that it might be possible to apply P&T with the aim of reducing the toxicity and lifetime of spent nuclear fuel.

8.4 Ongoing and Planned Research

The extensive research programme that has started in many countries in P&T is of a long-term nature. Basic research is mainly being conducted which provides a basis to judge which P&T concept is optimum with respect to efficiency, capacity, safety and economy under given technological and political conditions. The competence and infrastructure in the nuclear energy area that is required to develop a P&T capacity for spent nuclear fuel can be found primarily in the countries that have an active nuclear programme. For this reason, a short description of the nuclear power programmes in each country conducting research on P&T is provided as an introduction.

A common goal of research on P&T of spent nuclear fuel is to construct a demonstration facility in 10-20 years' time. The development of partitioning for spent nuclear fuel and particularly, of the method that is based on pyrochemistry is underway in parallel with this research.

8.4.1 European Research

In Europe, P&T research is being conducted, partly with economic support from the EU and within national programmes as well as within multinational programmes with or without the participation of the EU.

Multinational Projects

In the EU states, France, Italy and Spain are playing a leading role with respect to research on P&T. Jointly, these countries (the ministers of research in each country) took the initiative to propose a plan for research in the EU, with the aim to construct a demonstration facility for accelerator-driven P&T by 2012, followed by a prototype facility around 2030 which will lay the foundation for industrial facilities around 2040.

At a later stage, Belgium, Finland, Portugal, Sweden, Germany, Austria and EURATOM joined this multinational initiative. The work resulted in a report in 2001, which describes how a facility with an accelerator-driven system for transmutation could be constructed by 2010 (Eur 01). The work in the group was led by Prof. Rubbia. The report describes the ongoing projects in Europe which, together, comprise a broad research and development programme on the basic principles of accelerator-driven systems.

Another multinational project (Megawatt Pilot Experiment, MEGAPIE), which was initiated by laboratories in Switzerland, France, Italy and Germany with the participation of laboratories in the USA, Japan and South Korea, concerns the design and operation of one of the main components of an accelerator-driven system, namely, the equipment – the target – that delivers neutrons to the sub-critical reactor with the help of the accelerator. The equipment will be assembled and tested with a powerful accelerator which exists at a national laboratory (Paul Scherrer Institute, PSI), in Switzerland.

EU-funded Projects

The EU's support for P&T research has increased from about EUR 5 million in the third framework programme (1990-1994) to EUR 37 million in the ongoing sixth framework programme (2002-2006).

The EU has not officially adopted a position to the proposed plan from the group led by Prof. Rubbia, but is nevertheless following the proposed research plan from the group as a whole (Eur 01). A central project in this plan is a preliminary study of an accelerator-driven demonstration facility which was started during the fifth framework programme, 1998-2002.

Furthermore, during the fifth framework programme, the EU supported twelve projects divided in five clusters, all of which were co-ordinated under a joint thematic network for research on advanced options for partitioning and transmutation (ADOPT). In the twelve projects, basic research on partitioning, nuclear fuel for transmutation, nuclear physics data, technology and materials is being conducted as well as a preliminary study of an experimental facility for an accelerator-driven system. More than 50 institutes and laboratories, among them many from Sweden, were involved in these projects, several of which are still in progress.

The sixth framework programme (2002-2006) contains more projects than under previous framework programmes and covers a whole research area with detailed objectives. The aim is also to link up national research resources in networks and to encourage the mobility of researchers.

In particular one project in the sixth framework programme should be mentioned. The project aims at evaluating the impact of new technologies, especially P&T, on geological repositories both in terms of economy and radiological aspects. The project (Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Nuclear Waste Disposal) comprises 20 partners from leading organisations and research institutions in Europe and is being co-ordinated by Prof. W. Gudowski, Royal Institute of Technology, Stockholm. Non-technical factors and non-technical issues will also be dealt with in the project as well as the communication of results to the public.

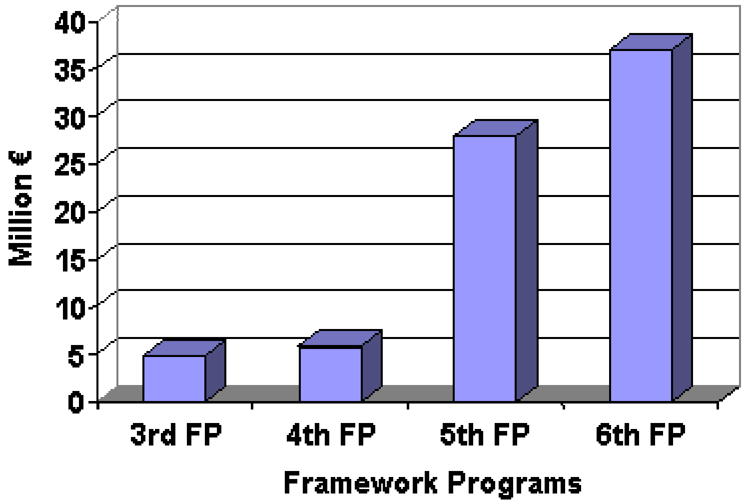

Figure 8.6. The budget for the EU's research programmes (framework programmes) for P&T from the third framework programme (1990-1994) to the sixth framework programme (2002-2006).

National European Project

Research on P&T is also being conducted on a national basis within certain EU countries (Jeju 02, SKI 03). The objective of this research is dependent on the nuclear energy programme of each country. The experimental rigs designed within these national programmes is often offered for use in international research in the EU or globally.

France

The national programme in France for nuclear waste management comprises three studies which have been stipulated in a French legal act from December 30, 1991. The act stipulates that a final report must be prepared for these studies so that the French parliament can make a decision in 2006 concerning a method for the management of the French nuclear waste. The first study focuses on method to substantially reduce the quantity and radiotoxicity of nuclear waste for a given energy production. The other study focuses on geological deep disposal without long-term human monitoring and the third on an interim surface disposal facility which requires permanent monitoring. The first study includes evaluations of the potential for P&T in available reactors or in innovative reactors, such as accelerator-driven sub-critical reactors. The report, which is to be submitted to the parliament, will be important to France's position on these issues and also for several other EU countries.

Some projects conducted by the Commissariat à l'Energie Atomique (CEA) can be specifically mentioned. In co-operation with the Italian nuclear energy organisation "Ente per le Nuove Technologie, l'Energia e l'Ambiente" (ENEA) two projects are underway to develop a powerful accelerator for transmutation and the connection between a sub-critical system driven by a smaller accelerator, where different fuels and coolants will be used, is also being studied.

Germany

Germany has a long tradition of research in the nuclear energy area through activities at institutions for nuclear physics and nuclear energy in Jülich and Karlsruhe. For European P&T research, the research at the Karlsruhe Lead Laboratory, (KALLA) is important. The research focuses on developing a method for the use of molten lead/bismuth as a reactor coolant.

In particular, corrosion problems and hydraulics are being studied. One of four research institutions operated by EURATOM is also located at Karlsruhe, namely the Institute for Transuranium Elements, (ITU) where research is conducted on the fabrication of fuel containing minor actinides (neptunium, americium and curium) and on pyrochemical partitioning methods.

Italy

In spite of the lack of nuclear reactors in Italy, quite extensive research is being conducted on P&T. This can partly be explained by the fact that Prof. Rubbia, who is Italian, is now the head of the ENEA. Rubbia and his group at CERN launched an accelerator-driven system (the "Energy Amplifier") in the mid 1990's which was intended to generate energy from thorium fuel instead of uranium. The advantage of thorium is that smaller quantities of transuranic elements (especially plutonium) are formed when this fuel is used. In addition, thorium is relatively plentiful in nature (considerably more so than uranium). The same type of accelerator-driven system, which was used for the "Energy Amplifier", can also be used for the transmutation of nuclear waste.

Three major projects are underway in Italy which are financed by the ENEA and conducted in co-operation with the CEA, France. The studies cover physics and technology for an accelerator-driven system for transmutation. The study is starting off with the accelerator for the system as well as a large-scale test of lead/bismuth as a coolant. A sub-critical TRIGA reactor is being used, operated by a cyclotron accelerator for testing the connection between these parts in an accelerator-driven system.

Belgium

A major experiment (MYRRHA) with an accelerator-driven system is also being planned in Belgium. As in Italy, the construction of an experimental facility has started. The facility comprises a powerful accelerator and a sub-critical reactor with plutonium fuel and different irradiation zones with fast and thermal neutrons. A bid for the facility is also being submitted for a joint project within the EU.

Russia

Russia plans to extensively expand nuclear power by 2020. Plans comprise the construction of 11 new reactors by 2010 with a total power of 10.8 GW and an additional 26 reactors by 2020 with a total power of 26.2 GW. As a result of this expansion, nuclear power in Russia will have a capacity of 360 TWh per year by 2020.

Furthermore, fast neutron reactors with liquid lead as a coolant have been studied in Russia (BREST-300 and BREST - 1200). The fuel cycle for this type of reactor (BREST) is such that the risk for nuclear arms proliferation is reduced, since no pure plutonium needs to be extracted from the spent fuel before it is returned to the reactor. Research is also in progress on the use of thorium fuel in molten salt reactors in co-operation with the USA and Japan.

The extensive research and development conducted in Russia in the nuclear technology area has generated knowledge about several types of reactors which are of interest for P&T research. This has resulted in a close co-operation on P&T research between Russian and western research groups, both via bilateral and multilateral agreements, and through an international organisation called the International Science and Technology Centre (ISTC).

The ISTC was jointly formed by the EU, Japan and the USA after the breakdown of the Soviet Union. The purpose of the ISTC is to financially support the transition to civil research at many nuclear weapons laboratories in the various former Soviet republics. This was conducted in order to counteract the spread of nuclear weapons expertise when Russian experts moved from these laboratories to countries wishing to acquire nuclear weapons. Several countries have provided financial support for the ISTC activities. Before Sweden joined the EU, the Swedish parliament decided to provide national support for the ISTC. In the case of Sweden, this support is now being channelled via the EU.

Several research projects on the transmutation of spent nuclear fuel have been financed by ISTC (SKI 03). Prof. W. Godowski, Department of Nuclear and Reactor Physics, Royal Institute of Technology – Stockholm, is the chairman of an advisory group to the European Commission concerning financial support from the EU to transmutation research projects. These projects comprise basic studies within a number of areas that are essential for the development of accelerator-driven transmutation. Project include nuclear physics data and calculation codes for accelerator-driven systems, development and manufacturing of equipment to produce an intensive neutron flux initiated by the accelerator's ion beam, studies of the properties of molten salts for reactor operation and partitioning and the construction of a research facility to study the link between an accelerator and a sub-critical reactor. The projects that are financed via grants from the EU to ISTC have been attached to corresponding projects – in terms of topic – conducted within the EU's framework programmes. In addition to the resulting knowledge exchange, the Russian research groups have improved their network of contacts in the west, which was previously largely non-existent.

One project at the Institute of Physics and Power Engineering (IPPE), Obninsk, which was originally initiated and financed by Swedish funds to the ISTC and which subsequently was also financed by the USA and the EU, deserves particular mention. The project concerned the design and manufacturing of equipment containing molten lead/bismuth for the production of an intensive neutron flux with the help of an ion beam from a high-energy accelerator. The equipment is a prototype of the neutron source that will drive a sub-critical reactor in an accelerator-driven transmutation system. The equipment was completed in 2001 and was planned to be irradiated at the high-energy accelerator at Los Alamos National Laboratory in the USA. For cost-related reasons, the irradiation was postponed indefinitely. The equipment is currently in a newly started laboratory for molten lead/bismuth at Nevada University, USA, where it is being used for teaching and research.

The national programme is financed by the Ministry for Atomic Energy (MINATOM) and comprises studies of transmutation with both critical and accelerator-driven sub-critical lead-cooled fast neutron reactors. The studies are based on experience from lead-cooled submarine reactors.

Czech Republic

For several years, a research programme on transmutation has been in progress in the Czech Republic. The programme, which is relatively ambitious, is based on the fact that it is difficult for the Czech Republic to find a suitable site for a geological repository within its national boundaries. A reduction of the nuclear waste quantities would mitigate this problem.

The research programme is focusing on the transmutation of spent nuclear fuel using a molten salt reactor, accelerator-driven or non-accelerator-driven. In this type of reactor, the fuel (spent nuclear fuel) is dissolved in the coolant, which is made of molten salts. The plan is to pump the fuel continuously into a loop through a partitioning stage where already transmuted material would be removed and the remainder returned to the reactor.

The research is being conducted in close co-operation with several Russian laboratories.

8.4.2 Research in the USA

Mr. Spencer Abraham, the US energy minister, informed the nuclear energy summit meeting in February 2002, held in Washington DC, on the plans for a new type of US-designed nuclear reactor which would be taken into operation in 2010. The initiative is being jointly taken by the US Department of Energy (DOE) and the private nuclear industry.

Furthermore, in 1999, the Nuclear Energy Research Initiative (NERI), was started. The main objectives and focus of the programme are as follows:

- The reactors and the fuel cycle will be designed to counteract the proliferation of nuclear weapons
- Advanced reactor systems
- Hydrogen gas production with nuclear reactors
- Basic nuclear energy research

Bilateral co-operation agreements have been signed with Canada, France, Brazil and South Korea. Negotiations for co-operation are underway with Great Britain and South Africa.

The US DOE is also leading the Generation-IV Reactor International Forum (GEN-IV) where considerable emphasis is being placed on optimising non-proliferation aspects, operating safety, economy, environmental aspects etc. Besides the USA, the participants are Great Britain, Switzerland, South Korea, South Africa, Japan, France, Canada, Brazil and Argentina. The work is based on demonstrating 6-8 promising reactor technologies and on presenting research and development needs with the aim of constructing a GEN-IV reactor system before 2030. In April 2003, the DOE published a report that shows the need for technological research and development in order to support the ongoing study of fourth generation reactors (DOE 03).

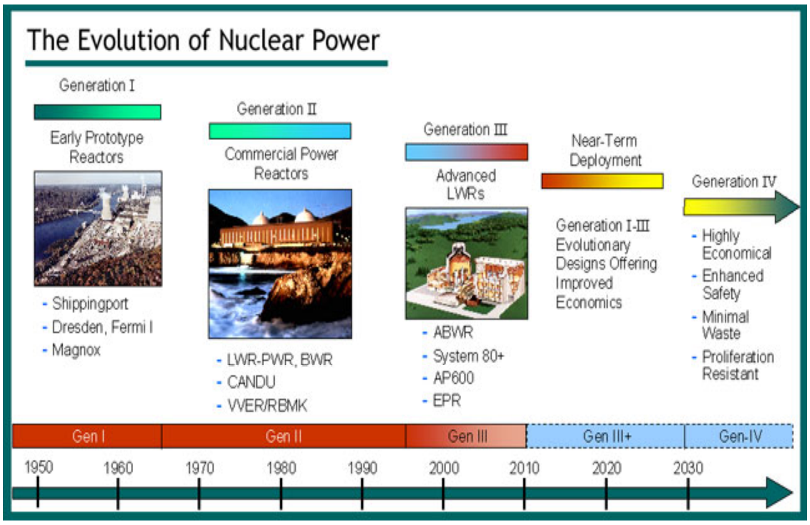

Figure 8.7. Reactor development up to the planned fourth generation of reactors.

In July 2002, Mr. Abraham also stated that Idaho National Engineering and Environmental Laboratory (INEEL) will be established as the USA's leading centre for nuclear energy research and development.

The US Congress has decided that a geological repository of nuclear waste in Yucca Mountain would be constructed. The repository is within the nuclear weapons testing area in the Nevada desert and is expected to be taken into operation in 2010. At this point, the repository will have just about adequate capacity to receive the waste quantities that will exist at that time in the USA. One way of avoiding having to identify new sites for new repositories and thereby the problems of obtaining public acceptance of these new repositories could be to radically reduce the waste quantities via P&T. In this way, Yucca Mountain would be adequate as the only waste repository for a long time into the future.

In the light of this, the US Congress requested that the DOE present a description of the technical possibilities and costs of using an accelerator-driven transmutation system to reduce the quantity of civilian reactor waste. The report was presented to congress in October 1999 (DOE 02). The report recommends the following phases towards the development and application of accelerator-driven transmutation technology:

- Phases with government funding:
  – R&D (2000–2008)
  – Followup of R&D (2008–2027)
  – Demonstration (2000–2027)
- Privatisation
  – Privatisation of the first facility (2023–2097)
  – Privatisation of several facilities (2027–2111)

As a result of the DOE's report, the Congress granted funding to the DOE for a programme for basic research on an accelerator-driven system for the transmutation of civilian nuclear waste. The research in the programme has involved national laboratories, universities and private industry. It includes research on different nuclear fuels, partitioning methods, coolants and materials.

A new programme (Spent Fuel Pyroprocessing and Transmutation) was started by the DOE in 2002 with a budget of USD 77 million. The programme focused on the development of methods for partitioning with pyrochemistry and transmutation of minor actinides. The research in this programme is largely being conducted at Argonne National Laboratory.

For the 2004 fiscal year, the DOE is applying for USD 63 million for the Advanced Fuel Cycle Initiative which is a continuation of the previous Spent Fuel Pyroprocessing and Transmutation programme. The aim of the programme is to develop methods for reducing the quantity and radiotoxicity of the spent nuclear fuel and, at the same time, reduce the long-term risk of plutonium proliferation. The programme is in harmony with the programme for the development of fourth generation nuclear reactors.

Los Alamos National Laboratory

Research on P&T started at the end of the 1980's at Los Alamos National Laboratory and was internally financed. The research focussed on accelerator-driven systems with molten salts (beryllium and lithium fluorides) where molten salts are the coolant in which the fuel is dissolved. A further refinement of this type of system is currently being provided by its inventor, Dr C. Bowman, through his private company, ADNA corp., since the Laboratory abandoned the concept as a main alternative for transmutation. Instead, the Laboratory was assigned by the DOE to develop an accelerator-based facility for the production of tritium. Within this project, which is also now abandoned, an injector for a highly powerful accelerator was developed. The injector is the component in this type of accelerator that presents the greatest technological problem. Research on this injector, on radiation damage in the material and on the molten lead-bismuth is the Laboratory's current contribution to the DOE's programme on transmutation.

Argonne National Laboratory

Argonne National Laboratory is responsible for the development of pyrochemistry for P&T and fission products in the DOE's programme. Furthermore, a programme for the development of fuel for an accelerator-based transmutation system, in terms of fabrication and fuel testing, is also included.

General Atomics

A thermal, or more correctly, an almost thermal reactor has been proposed by a group at General Atomics for one-step burning of the high-level part of spent fuel. Only uranium is separated from the spent nuclear fuel. The reactor (Modular Helium Reactor) is cooled by helium gas and has a graphite moderator. The fuel comprises small particles (TRISO-coated particles) where a small quantity of the spent nuclear fuel is surrounded by a robust sphere of ceramic material that can withstand very high radiation doses. After about two years of irradiation, it is estimated that about 80 % of the spent nuclear fuel will be transmuted. The particles are well suited to subsequent geological disposal.

8.4.3 Research in Japan

The Japanese parliament made a decision in May 2000 that spent nuclear fuel with or without prior transmutation would be deposited in a geological repository which would be ready for use some time between 2030 and 2040. At the same time, extensive research is being conducted on P&T of spent nuclear fuel in order to recover energy and materials resources contained in spent fuel (Jeju 02).

In Japan, a programme to develop technology and methods for the optimum use of spent nuclear fuel – nuclear waste (Options Making Extra Gains from Actinides and fission products, OMEGA) was started in 1988. The first phase of the programme, which aimed at evaluating different concepts and conducting research and development on key technologies has been completed.

Phase two of the long-term OMEGA research programme concerns P&T and the final report is to be made in 2005. The work within this phase of the programme comprises technical research and the demonstration of some key technologies for transmutation. Furthermore, funds have been granted (USD 1,800 million) to construct a powerful accelerator (Japan Proton Accelerator Research Complex, J-PARC) in co-operation with the university of Kyoto. The accelerator is to be used for university-related basic nuclear physics research and for research on transmutation. For the latter, two experimental rigs are being constructed at the accelerator, one for radiation damage studies on materials and the other for studies of the connection between an accelerator and a sub-critical reactor. The accelerator facility is expected to be taken into operation in 2008. In phase two of OMEGA, research and development will also focus on partitioning methods based on both water chemistry and pyroprocesses.

8.4.4 Research in South Korea

South Korea currently has 16 nuclear power reactors in operation with a capacity of 12.9 GWe and four under construction. Up to the end of 2001, 5,300 tonnes of spent nuclear fuel had accumulated. Three different methods of handling the spent nuclear fuel were studied and, for the time being, the fuel is being interim stored at the reactor sites. The three methods being studied are direct disposal in a geological repository, waste burning in a Canadian-type heavy water reactor (CANDU reactor) and P&T. P&T is being conducted using pyroprocesses and is being followed by burning in a fast neutron reactor or in an accelerator-driven system.

The Korea Atomic Energy Research Institute (KAERI) is constructing a large-scale test facility for accelerator-driven transmutation (Hybrid Power Extraction Reactor, HYPER) (Jeju 02). The sub-critical reactor will have a power of 1,000

MWth and is the most powerful test facility in the world for accelerator-driven transmutation. Phase two of the HYPER project is expected to be completed in 2004 and comprises the testing of key technologies, the analysis of accelerator reactor-integrated systems and the development and testing of computer codes. Phase three of the project which will lead to final design drawings for the HYPER system, is expected to be conducted from 2005 to 2007. It is planned that the facility will produce both fast neutrons for the transmutation of transuranic elements and thermal neutrons for the transmutation of fission products. Research and development of pyroprocesses for the partitioning of the long-lived radioactive substances in spent nuclear fuel is being conducted in parallel with the design and construction of HYPER

8.4.5 International Atomic Energy Agency (IAEA)

At the UN summit meeting in New York on September 6, 2000, President Putin declared that sufficient electricity must be generated globally to enable the sustainable development of humanity. Nuclear power has a role in this context, he stated, but a solution must be found to the problem of the nuclear arms proliferation which is associated with this energy source. As a result of this move, the UN's International Atomic Energy Agency (IAEA) in Vienna initiated a programme with the aim of developing nuclear technology that does not require or produce weapons-grade material and of studying methods for burning (transmuting) long-lived spent nuclear fuel. The programme, INPRO, was launched in May 2001 and has 16 members from 14 different countries and international organisations. Sweden is not participating in the programme.

Apart from this, the IAEA arranges several international research programmes (Coordinated Research Programmes [CRP's]), specialist meetings and a database for research relating to accelerator-driven transmutation.

8.4.6 OECD Nuclear Energy Agency (OECD/NEA)

Two committees in the OECD/NEA (the Nuclear Development and Nuclear Science committees) have, together with the NEA's Data Bank, started a number of technical and strategic studies concerning P&T. An expert group comprising 37 experts from 15 member countries published a comparative study between accelerator-driven systems and fast neutron reactors for transmutation (NEA 02).

In co-operation with the IAEA and the EU, the OECD/NEA is arranging a series of meetings on the P&T of actinides and fission products (Information Exchange Meetings on Actinide and Fission Product Partitioning and Transmutation). The seventh meeting in the series was held on October 14 to 16, 2002 at Jeju in South Korea (Jeju 02).

8.4.7 Swedish Participation in International Research

Swedish research work on P&T is based on the interest that research groups at Chalmers University of Technology (CTH), the Royal Institute of Technology (KTH) and Uppsala University have shown in the research area (SKI 03). The subject specialisations of the research groups complement each other so that a relatively good coverage has been achieved of the technical areas that are relevant for P&T. The focus of research at CTH is nuclear chemistry, at KTH, reactor physics and at Uppsala University, basic nuclear physics data. Research on P&T has also resulted in an increase in the number of research students who have been attracted to academic studies in the nuclear field.

At a symposium in Italy in 1990, a research group from Los Alamos National Laboratory (LANL), USA presented a concept for accelerator-driven P&T of nuclear waste which launched Swedish research in the area. Sweden then responded positively to a query from the same research group at LANL regarding whether Sweden could host a specialist meeting on P&T in 1991

(KAS 92). Researchers, not only from the USA and Sweden but also from Russia, were specially invited to the meeting, which was arranged in Saltsjöbaden by the then Swedish National Board for Spent Nuclear Fuel (SKN) in co-operation with LANL. The meeting agreed to support and guide Russian research groups with a unique competence in several research areas of relevance for P&T research in their applications for financial support for this type of research to the newly established International Science and Technology Centre (ISTC) in Moscow (see Section 8.4.2). This led to the involvement of the research groups from CTH, KTH and Uppsala University in several Russian projects on P&T where a few are specified under the description below of ongoing research at each university. Financial support, primarily for travel, was granted to the university research groups during the period from 1996 to 2002 from the Swedish Nuclear Power Inspectorate (SKI) to manage and report on the contacts with the Russian groups (SKI 03).

The research groups at CTH, KTH and Uppsala University have interacted on an informal basis. The groups applied for financial support from the Swedish Foundation for Strategic Research to form a Swedish centre for transmutation research. The application was rejected after a long period of evaluation. The groups jointly arranged the second international conference on accelerator-driven transmutation research in Kalmar in 1996 with 217 participants from 23 countries and four international organisations (Kal 96).

At an early stage, the groups from CTH, KTH and Uppsala University became involved in P&T research in the EU framework programme. The Swedish Nuclear Fuel and Waste Management Co (SKB) and the Swedish Centre for Nuclear Technology at KTH also support P&T research at the university research groups mentioned in the form of an annual grant of about SEK 6 million (SKB 04). The justification provided by these supporting bodies for their financial support of P&T research is the development of knowledge to monitor foreign research and the side effect of training qualified nuclear engineers for Swedish authorities and the nuclear industry. SKB is also particularly monitoring Swedish participation in P&T projects in the EU's framework programmes and, since 2003, in ISTC projects with the same research focus.

Chalmers University of Technology

The Department of Nuclear Chemistry is participating in an EU project (PARTNEW) within the fifth framework programme. The contribution from the Department is primarily to develop aqueous chemistry methods for partitioning the heaviest transuranic elements, americium (Am) and curium (Cm) from high-level waste. The partitioning occurs in stages where first Am/Cm are separated together with a series of elements called lanthanides. In a second stage, Am/Cm are separated from the lanthanides. For this process, the CTH group has studied different extraction chemicals with the aim of also minimising the waste streams. With the support of SKB, the possibility has also been studied of separating the transuranic element neptunium and the long-lived fission products, technetium and iodine, in connection with the process (PUREX) that is used at the commercial P&T facilities in France and England for the separation of plutonium from spent nuclear fuel.

Royal Institute of Technology, Stockholm

In 2001, the Royal Institute of Technology (KTH) decided to establish the Centre for Nuclear Technology for training and research in the area, comprising the departments for nuclear technology, reactor physics, reactor technology, reactor safety and nuclear chemistry. In the Department of Nuclear and Reactor Physics, a professorship in reactor physics with transmutation was awarded in 2001. The professorship is held by W.

Gudowski. Professor Gudowski has, and has been, entrusted with a large number of commissions relating to international P&T research. He has been consulted as an adviser on research issues by the US Department of Energy (DOE), Commissariat à l'Energie Atomique (CEA), France, Russian Ministry of Atomic Energy (MINATOM), Moscow, Korean Atomic Energy Research Institute (KAERI), South Korea, European Commission (EU), Brussels, International Atomic Energy Agency (IAEA), Vienna etc.

At the Department of Nuclear and Reactor Physics, several research projects are being conducted within the EU's fifth framework programme and with financial support from SKB and the Swedish Centre for Nuclear Technology. The Department is managing an EU project (CONFIRM) which aims at developing and irradiating fuel for the transmutation of transuranic elements. The irradiation is to be performed in the R2 reactor at Studsvik. Radiation damage studies on special types of steel are being conducted within the EU projects, SPIRE and MUSE. Together with the Department of Reactor Safety, the Department of Nuclear and Reactor Physics is also participating in preliminary studies in an EU project (PDS-XADS) concerning an accelerator-driven system. A test loop for liquid lead/bismuth has also been built at the Department of Nuclear Safety for research in connection with an EU project (TECLA).

As mentioned in Section 8.4.1 – EU-funded Projects – W. Gudowski is co-ordinating a project within the sixth framework programme which aims at evaluating the impact of new technologies, especially P&T, on geological repositories, both in terms of economy and radiology. The project – Impact of Partitioning, Transmutation and Waste Reduction Technologies on the Final Nuclear Waste Disposal – comprises 20 partners from leading organisations and research institutions in Europe. Non-technical factors and non-technical issues as well as the communication of results to the public will also be dealt with within the project.

The aspects of serious accidents in transmutation facilities has been studied in co-operation with EURATOM's research centre at Ispra, Italy and at the university in Bilbao, Spain.

The Department of Nuclear and Reactor Physics is also participating in a number of Russian projects where the Russian research work is being funded by the International Science and Technology Centre (ISTC), Moscow. In particular, the department has been involved in the previously mentioned project at the Institute of Physics and Power Engineering (IPPE), Obninsk, which concerned the design and manufacturing of a prototype for an intensive neutron source for the operation of a sub-critical reactor in an accelerator-driven transmutation system (described under the heading of *Russia* in Section 8.4.1). Professor Gudowski is the chairman of the experiment committee and Swedish researchers are invited to participate in the research work on the equipment.

Some of the ISTC projects in which the Department of Nuclear and Reactor Physics is participating include experimental studies of molten salt reactors in an accelerator-driven system for the P&T of civilian radioactive nuclear waste and military plutonium at the Institute of Technical Physics (VNIITF), Snezhinks, in the Chelyabinsk region. Furthermore, construction of a subcritical system driven by an accelerator for the study of the connection between the two components in an accelerator-driven transmutation system at the Joint Institute for Nuclear Research (JINR). In addition, the Department is also participating in projects with the aim of developing and testing databases and calculation codes for transmutation as well as studies of materials-related issues in connection with transmutation.

Extensive theoretical studies have also been conducted by an accelerator-driven system with liquid lead/bismuth as a coolant for the transmutation of Swedish nuclear waste (Wal 01). The sub-critical reactor has a high share of plutonium in the fuel and burnable absorbers in order to achieve an even burnup throughout the core. A study has also been conducted on the costs of

P&T to identify the parts of the system that determine the costs as a whole (Wes 01). An estimate has also been made of the production costs of electricity generated by nuclear reactors which contain an accelerator-driven system for transmutation of spent nuclear fuel. Some of the results of this study are presented in Section 8.5.

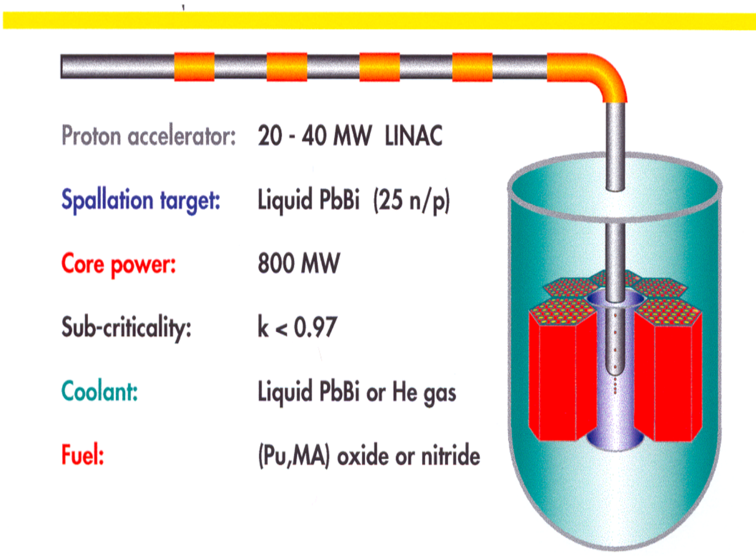

Figure 8.8. Illustration of a transmutation facility for Swedish spent nuclear fuel according to studies conducted at the Department of Nuclear and Reactor Physics at the Royal Institute of Technology, Stockholm (ref. Wal 01).

Uppsala University

Activities at Uppsala University largely focus on measurements of nuclear physics data for transmutation. The work is being conducted at the Department of Neutron Research (INF) and has been jointly financed since July 2002 by SKB, SKI, FOI (the Swedish Defence Research Agency) and Ringhals Nuclear Power Plant/Barsebäck Kraft AB. The four-year project includes two doctoral students. This project follows a similar four-year project conducted in 1998-2002 with the same sponsors and which resulted in two PhD theses.

Experimental research is being conducted at the The Svedberg Laboratory's (TSL's) cyclotron and is focusing on studies of neutron scattering in different materials of interest for accelerator-driven transmutation technology. The INF is also participating in an EU project within the fifth framework programme which aims at meeting the need for nuclear physics data for accelerator-driven transmutation systems. 16 laboratories from seven countries are participating in the project, which is entitled "High and Intermediate Energy Nuclear Data for Accelerator-Driven Systems, HINDAS". Experimental groups from Germany and France participating in the HINDAS project are conducting their experiments at TSL in co-operation with the INF.

A research group from the Khlopin Radium Institute, S:t Petersburg has measured, at TSL, fission cross-sections (the probability that fission will occur) which are of importance for accelerator-driven transmutation in co-operation with the INF and with the financial support of ISTC. Similarily, with the support of ISTC, experiments at TSL are being planned by a group from the Institute for Theoretical and Experimental Physics (ITEP), Moscow, to determine nuclear physics properties of materials of interest for the transmutation of nuclear waste.

In 2002, the Swedish Research Council decided to terminate financial support to two national laboratories, namely the The Svedberg Laboratory in Uppsala and the Manne Siegbahn Laboratory in Stockholm. The decision was made for budget-related reasons. For the some 50 doctoral students who are dependent on TSL to complete their studies, an agreement has been concluded between Uppsala University and the Swedish

Research Council concerning a successive reduction of the Council's 50 % grant for the operation of the Laboratory over a three-year period. At the same time, the possibility of finding sponsors for future applied research at the Laboratory is also being investigated. TSL offers a unique opportunity to conduct research on accelerator-driven transmutation. Consequently, a closure of the Laboratory would drastically affect national research in this area.

8.5 Scenarios

8.5.1 Components in the P&T System

The main components of a transmutation system based on the two-stage concept is presented below, as described in Section 8.2.5 *Technical Alternatives*:

1. Nuclear plants that account for a large part of the country's power production. These may be conventional nuclear power plants of the type that we have at present in Sweden, but may also be newer types of reactors, which also function as transmutation facilities (see also point 5, below);
2. A reprocessing facility where the spent nuclear fuel from nuclear power plants is chemically treated;
3. Fuel fabrication plants where MOX fuel is manufactured for nuclear power plants;
4. Fuel fabrication plants where fuel for transmutation facilities is manufactured. Besides plutonium, this fuel also contains the other transuranic elements that are to be transmuted;
5. Transmutation facilities where the plutonium that can no longer be recycled for fresh MOX fuel for thermal reactors as well as other transuranic elements and fission products are transmuted. In certain cases, the fission products are transmuted through irradiation in thermal reactors or are directly deposited as waste in a geological repository;

6. A partitioning facility, in accordance with the pyrochemical method for irradiated fuel from the transmutation facilities;
7. Small geological repositories for certain elements which could not be transmuted as well as for the high-level waste streams from the separation processes.

For transmutation based on the single-stage principle, the three first points above are not relevant and would be replaced by a single partitioning facility, as described in point 6 above, where all of the irradiated fuel would be treated, including fuel from conventional nuclear power plants.

8.5.2 Three Scenarios

To more clearly describe how transmutation could be applied in a future Swedish energy system, three different scenarios are described in this section. These scenarios have been selected so that they include a broad range of possibilities. However, they are by no means exhaustive. The three transmutation scenarios are

A: A system where Sweden itself acquires all of the required resources, without depending on services purchased from abroad;

B: A system where Sweden uses the technology and resources that have been developed in the leading and prominent countries with nuclear power programmes;

C: A compromise, where Sweden sends its spent nuclear fuel for partitioning and fuel fabrication abroad and then conducts, in Sweden, transmutation of the material that is returned from the partitioning facility.

Scenarios A and C assume that Sweden will continue to invest in the development of nuclear power in Sweden, while Scenario B could also possibly be applied in combination with a phase-out of nuclear power in Sweden.

Scenario A: An exclusively Swedish transmutation system

It is possible to imagine variations on a future nuclear energy system.

One example (the two-stage principle) could be to continue with thermal reactors, more or less of the same type that currently exists (see point 1 in the component list in Section 8.5.1), together with one or several transmutation facilities (point 5) based on fast sub-critical systems. Most of the Plutonium will be burnt as MOX fuel in the conventional reactors, while the remaining plutonium and other transuranic elements will be treated in the transmutation facilities. This alternative would require a reprocessing plant (point 2) as well as a fuel fabrication facility (point 3) where MOX fuel is manufactured for the nuclear power plants. In addition, a partitioning facility would be required (point 6), based on pyrochemistry for irradiated fuel from the transmutation facilities as well as a fuel fabrication plant where fuel from the transmutation facilities is manufactured (point 4). The fission products, apart from certain long-lived products which are transmuted, will be sent directly for disposal (point 7) as also certain remaining high-level waste streams that are generated due to the fact that the P&T processes are not one-hundred per cent efficient.

A second alternative (single-stage process) is to separate the plutonium and other transuranic elements from the spent nuclear fuel in a partitioning facility (point 6), based on pyrochemistry. The fuel, comprising plutonium and other transuranic elements, is manufactured in a fuel fabrication plant (point 4) from where the fuel is then sent to transmutation facilities (point 5). As in the first alternative, the fission products, apart from long-lived products, are sent directly for disposal (point 7). The reprocessing plants (point 2) and the MOX fuel fabrication plants (point 3) are therefore not relevant.

Estimates show that one single transmutation facility would manage to "clean up" after about seven conventional reactors if the plutonium is recycled to the reactors in accordance with the two-stage principle, while the corresponding capacity in accordance with the single-step principle is five conventional reactors. At the same time, the transmutation facility produces about 500 MW of electricity, of which the facility itself consumes about 40 MW for the operation of the accelerator. If the aim is to quickly reduce the inventory of spent nuclear fuel which has accumulated in the Central Interim Storage Facility for Spent Nuclear Fuel (CLAB) over the years, one or more additional transmutation facilities will be needed.

***Scenario B:** A system where Sweden completely depends on the technology and resources developed within the leading countries with nuclear power programmes*

In this scenario, Sweden has not constructed its own facility for any part of the transmutation process. All services are purchased from abroad. Two different cases are therefore envisaged: one with the continued operation of thermal reactors in nuclear power plants and a second where nuclear power is no longer used in Sweden.

Scenario B1: Continued operation of thermal reactors

If Sweden continues to use its thermal reactors or to construct new reactors of the same type, spent nuclear fuel can be sent for reprocessing abroad and the plutonium can be returned to Sweden in the form of MOX fuel which is used in Sweden's own reactors and which is subsequently again sent abroad for reprocessing etc. The transmutation of transuranic elements and fission products is conducted abroad and the residual products that must be handled for disposal are returned to Sweden where they are deposited in a geological repository. The requirements on this repository, in terms of volume and protection over very long timescales, are considerably less than the corresponding requirements for the spent nuclear fuel repository that is currently being planned. In Sweden, only the facilities listed in point 1 and 7 would be required. For the rest of the treatment and handling, Sweden would depend on services purchased from facilities abroad.

It can be said that this variation partly corresponds to the principle for waste management that applied at the start of the Swedish nuclear power programme when Swedish spent nuclear fuel was sent abroad for reprocessing. Plutonium and reprocessing waste would then be returned to Sweden after reprocessing.

Scenario B2: No further nuclear power production in Sweden

In this case, Sweden has no possibility of using the plutonium that comprises a large part of the long-lived radioactivity in spent nuclear fuel. This plutonium must be exported and all transmutation occurs abroad. The only work that Sweden can conduct is – as in the first alternative – to manage the waste and deposit it in a repository in Sweden (point 7).

With scenario B1, it can still be claimed that Sweden to some extent fulfils the principle that it should take care of its own nuclear waste, although this is not the case with scenario B2. Furthermore, Sweden cannot force any other country to assist Sweden in managing its nuclear waste in the way described here. However, different countries are free to voluntarily enter into agreements regarding co-operation and trade in services within this area, if they should so wish. An important complication is that, with scenario B2, Sweden must send all of its plutonium abroad. Such an activity must be safeguarded by rigorous safety regulations to ensure that the material cannot go astray under any circumstances.

Scenario C: Partitioning and fuel fabrication abroad, transmutation in Sweden

A system where Sweden sends the spent nuclear fuel abroad for reprocessing and receives MOX fuel for Swedish thermal reactors and ADS fuel for Swedish transmutation facilities represents a compromise between scenarios A and B. The situation is assumed to be about the same as for scenario A with respect to the reactor park (point 1), including transmutation facilities (point 5). No Swedish facilities for reprocessing fuel from light water reactors (point 2) or from the transmutation facilities (point 6) have to be built. Furthermore, fuel fabrication plants for MOX fuel fabrication (point 3) and ADS fuel (point 4) are not relevant. A geological repository is necessary as in the other scenarios (point 7).

With this scenario, it could be claimed that Sweden is itself taking care of its own waste, since Sweden – exactly as in scenario 1 – will be burning most of the plutonium in its thermal reactors, transmuting other plutonium and other transuranic elements in transmutation facilities and managing fission products and other waste streams for disposal in a repository in Sweden.

8.5.3 Costs

Attempts have been made to estimate the cost of an accelerator-driven transmutation system in a report prepared at the Royal Institute of Technology, Stockholm (Wes 01). These estimates are based on attempts to estimate the cost of each step in the handling and to, subsequently, add the different items. It should be remembered that some of the cost items concern stages that entail untested technology and that more precise knowledge of the cost is therefore not available. When estimating the cost of untested technologies, a standardised approach was taken based on the usual progression of the cost of new technology as new technology is applied and tested. It should also be noted that the costs concern an activity that is conducted on a sufficiently large scale to be financially feasible.

For purposes of comparison, the electricity generation cost for a system where the fuel was only used once (as in the current Swedish system) and subsequently disposed of without reprocessing was estimated at about SEK 0.20/kWh, while the corresponding figure for a transmutation system in accordance with the two-stage principle was estimated at about SEK 0.27/kWh. For a system based on a single-step principle, namely without MOX recycling to thermal reactors, where the thermal reactors are operated using enriched uranium, as is currently the case, and where all transmutation occurs in ADS facilities, the cost would be about SEK 0.30 /kWh. In the report, the amounts were given in USD. An exchange rate of SEK 8/USD has been used here. The estimate includes the cost of

- the light water reactor fuel;
- the capital cost of the light water reactors;
- the operation and maintenance of the light water reactors;
- the manufacturing and reprocessing of the ADS fuel;
- the capital cost of the ADS facilities;
- the operation and maintenance of the ADS facilities;
- the waste disposal.

No production taxes, fees to nuclear waste funds or suchlike have been included in the calculation.

The report also reaches the conclusion that even if the production cost of nuclear power, with the systems that include ADS transmutation, should prove to be more expensive than the basic scenario (with direct disposal of spent nuclear fuel), the electricity generation cost is still competitive with many of the alternative power production technologies that are available (for example, less expensive than natural gas-operated turbines, wind power plants and bio energy-based combined heat and power; more expensive than coal or natural gas-fired condensing power).

A rough estimate shows that these calculations indicate that the waste in a nuclear power system involving transmutation would cost about 30 % of the total energy production. This figure can be compared with the corresponding figure for the KBS-3 system which is about 5 %.

8.5.4 Discussion of the Scenarios

Some of the facilities listed in Section 8.5.1 are based on a relatively well-developed technology and already exist. Others are at the research or development stage.

Thus, the reprocessing of conventional reactor fuel (point 2) and the fabrication of MOX fuel (point 3) are relatively well-established technologies with facilities that work (abroad). Final disposal technology (point 7) is being developed internationally with Sweden as one of the leading countries.

With respect to the fabrication of plutonium-based fuel – which should also contain additional highly powerful radioactive transuranic elements – facilities are required with very good radiation protection and a special fabrication method (point 4 and point 6). Physically, the fuel for the transmutation facility also has another form than traditional light water reactor fuel, for instance thinner fuel pins. Fuel fabrication for transmutation facilities therefore requires a special manufacturing facility or at least a special manufacturing line. Such fuel manufacturing must also be conducted on a certain minimum scale in order for the handling to be financially feasible. However, the construction of a manufacturing line exclusively to provide a limited number of Swedish transmutation facilities with fuel could be relevant if Sweden continues to use nuclear power or if the facility could serve an adequately large foreign market. No developed method for manufacturing such fuel yet exists, although development work is underway in several countries. From a transport perspective, it would of course be a considerable advantage if this special fuel, intended for transmutation facilities, could be manufactured directly in connection with the partitioning facility.

Partitioning facilities, as described in point 5, are being developed in different parts of the world as shown in Section 8.4. It is obvious that development work will occur in the leading nuclear countries. It still remains to be demonstrated that the proposed method can be made reliable and feasible.

In general, it can be said that all arguments about the transmutation of nuclear waste are based on the assumption that nuclear power production will continue. Transmutation facilities must also be allowed to generate electricity in order to achieve a reasonable economy for waste transmutation.

The description of the transmutation method that is provided in this chapter may be considered to be characterised by a relatively optimistic view of the technology and its development. It is difficult to avoid this when describing new technology that is under development.

If a comparison is to be made between transmutation and the direct disposal system which is currently being planned for Sweden, it should be remembered that two methods at different stages of development are being compared and that the comparison could therefore be deficient. However, even if final disposal technology is not completely developed in all respects, more is known and understood about final disposal technology than about P&T.

P&T of spent nuclear fuel entails extensive handling. Spent nuclear fuel is treated in a series of chemical processes, new fuel is fabricated, irradiated, reprocessed etc. This means that the personnel working with the processes will be exposed to radiation. It is not a question of unmanageable doses, however, the fact remains that it is possible that people will be exposed to greater doses than in the “Swedish system” with direct disposal in a repository in the bedrock. P&T also entails a greater risk for increased radioactive releases to the environment. In turn, this can lead to people and other species outside the facility being exposed to increased radiation doses. The advantage of direct disposal, compared with management that is based on transmutation, is that spent nuclear fuel will be handled while it is well encapsulated in canisters and this will provide an effective radiation shield in the repository and prevent radioactivity from being released to the external environment in connection with deposition.

One view that has been put forward by advocates of P&T is that the quality of the plutonium in a repository for spent nuclear fuel for weapons manufacturing improves with time, since the concentration of plutonium-239 increases as heavier plutonium nuclei undergo radioactive decay. The repository would therefore be of interest for terrorists wanting to appropriate weapons-grade material. However, it should be remembered that the repository does not contain pure Plutonium. The material still needs to be reprocessed in order to separate the plutonium from the residual uranium etc. However, this should be possible in a small facility and should therefore – at least in principle (which also applies to small-scale uranium enrichment) – be a way for terrorists to gain access to fissile material which can be used in nuclear explosives.

The question of which method is preferable – direct disposal or P&T – from the standpoint of the non-proliferation of material that can be used to manufacture weapons cannot be answered unequivocally and in general terms. The answer depends on the specific system that is being discussed. The partitioning of plutonium from spent nuclear fuel with the aim of fabricating MOX fuel (which is included in the two-stage principle above), means that plutonium in a form which may be suitable, accessible and treatable for the purpose of manufacturing weapons occurs in the handling chain. In view of this, it may in spite of everything appear to better – from this standpoint – to directly dispose of the spent nuclear fuel.

If, on the other hand, the single-stage principle is chosen, the spent fuel can be treated in a partitioning facility where the uranium is removed and all of the plutonium can be allowed to be included in the same stream as other transuranic elements. This product, which will then comprise the raw material for fuel manufacturing for the transmutation facilities, is considerably less suitable for handling without advanced equipment. Plutonium in a suitable form will therefore not be accessible at the early stage of handling or in the repository.

In connection with the development of fourth generation reactors (see for example, Section 8.4.2), particular emphasis is placed on optimising non-proliferation and environmental aspects.

With respect to the utilisation of resources, namely how the total inventory of uranium in the Earth's crust and seas is used, it has often been pointed out that existing reactors only utilise a negligible part of uranium's energy content and that, with direct disposal of spent nuclear fuel, large energy resources are allowed to follow the waste directly to the repository. This is certainly true, but for reasons described above (a plentiful supply of uranium at a low price, access to large quantities of plutonium which can be used for fuel fabrication etc.), this does not appear to be a major problem at present.

It has also been pointed out when discussing transmutation facilities (ref. Wes 01) that the extensive handling of lead which could arise with a transmutation facility would require a change in Swedish environmental legislation.

Comment

The account provided in this chapter of this state-of-the-art report shows that P&T of nuclear waste is based on nuclear principles and methods which include the use, not only of accelerators but also of nuclear reactors. Discussing how such technology could be used in a country where a decision has been made to phase-out nuclear power is a somewhat delicate undertaking, at least if it is assumed that the activity will be conducted in Sweden since Sweden wishes to fulfil its intentions that Sweden must take care of its own waste in Sweden. Naturally, KASAM has no reason to question the decisions that have been made concerning the future of nuclear power in Sweden. However, a discussion on various possible ways of applying transmutation technology to Swedish waste, must include scenarios where nuclear power plants are still in operation, either those of a conventional type, together with special transmutation facilities (two-stage principle) or also only transmutation facilities (single-stage principle). In practice, the latter are a combination of nuclear waste incineration facilities and nuclear power plants.

8.6 Concluding Remarks

The previous section describes three scenarios. The purpose of these scenarios is to show how transmutation technology can be used in different ways to manage spent nuclear fuel from Swedish nuclear power plants.

A number of conditions must be met for the technology to be applied in Sweden.

Conditions

- For transmutation technology to be applied to nuclear fuel from Swedish nuclear power plants, the Swedish policy on the use of nuclear power and the disposal of nuclear waste must be changed and the Act on Nuclear Activities amended. If not, Sweden must rely on the possibility that these services can be purchased abroad.
- The development of transmutation into an industrial technology requires extensive development work over a long period of time (about 30 years according to the EU's

research and development plan). The development work must therefore be conducted through international co-operation. This also applies to Swedish research and development work.

- Four completely new types of nuclear facilities must be developed: An accelerator, a reactor, a reprocessing plant and a fuel fabrication plant. All of these facilities must work efficiently with each other (efficient separation of short and long-lived radionuclides), a high level of safety for personnel and the environment and at a reasonable cost.
- Only when prototypes of these facilities are in operation, in 20 to 30 years, can a more accurate evaluation be made of efficiency, safety, cost etc. Only then is it meaningful to decide whether or not transmutation is of interest as a viable alternative.
- Transmutation technology assumes that at least two reactors of a new type will be constructed for the conversion of Swedish nuclear waste over a reasonably long period of time (30 years).

Investing in transmutation entails investing in nuclear technology with the advantages and disadvantages that this involves. What are these advantages and disadvantages?

Advantages

- P&T is based on known principles and scientific facts. No scientific breakthrough, as for fusion (hydrogen energy) is necessary.
- *For most of the transmuted nuclear waste*, the assumption is that the radioactivity can decay to non-hazardous levels within about 1,000 years. This can be compared with the several hundred thousand years that are necessary for spent nuclear fuel, which has not been reprocessed or transmuted, to become equally as non-hazardous. This simplifies the

construction of a repository and reduces the risk of radioactive releases from the repository. This argument assumes that the remaining quantity of long-lived radionuclides in the main fraction will be very small. However, it should be emphasised that even with transmutation, facilities of the same type as in the current Swedish nuclear waste programme, will be needed even if the repository can be made considerably smaller and does not require the same level of robustness over time.
- An investment in transmutation means that it will be possible to maintain nuclear expertise for a long time.
- Through transmutation, the quantity of plutonium that could be used for nuclear weapons manufacturing is burnt up, at the same time that energy can be recovered. (However, compare this with the first point below).

Disadvantages

- P&T, in the form which entails plutonium incineration in the form of MOX fuel (see Section 8.5), assumes reprocessing before incineration. This increases the releases to the environment and increases the risk of nuclear arms proliferation. – Swedish policy is to not reprocess spent fuel.
- The new reactors could be built in Sweden. However, it is uncertain whether it would be possible for this to be accepted during a nuclear power phase-out period. The new reactors could also be built outside Sweden. However, this assumes that some other country is willing to support such an arrangement. – This could be perceived as though, to some extent, Sweden is departing from the principle that each country should take care of its own waste.
- It is hardly technically or economically feasible for Sweden to construct the partitioning facility or facilities that are required for P&T. Therefore, a condition will be that

partitioning can jointly be conducted between countries in a number of European facilities.

- The number of transports in Sweden and abroad will increase. This can entail increased risk.
- In order to achieve transmutation technology at a feasible cost, it must be possible to also use the reactors that are constructed for the production and supply of electricity. Even with power production, transmutation can be expected to result in a considerably more expensive handling of nuclear waste than direct disposal which is currently being planned. – If the costs of direct disposal are about 5 % of the cost of the electricity generated, the corresponding cost of treating the waste through transmutation will be about 30 % of the cost of electricity generation, according to Swedish calculations. According to the same calculation source, the latter higher electricity generation cost corresponds to that for alternative energy sources such as wind and biofuel.

Conclusions

The application of P&T to Swedish nuclear waste will be a question for future generations. With present-day knowledge of this technology, it is not acceptable to interrupt or to postpone the Swedish nuclear power programme, citing P&T as an alternative. On the other hand, this possible future alternative reinforces the requirement that the repository should be designed so that waste retrieval is possible. According to the ethical principles that KASAM and others have established, each generation should take care of its own waste and not force future generations to develop new technologies to solve the problems. Therefore, it is reasonable for resources to be put aside for further research on P&T. This research could also pay off in ways which are of value for other areas, such as nuclear physics, chemical partitioning technology and materials technology. Swedish P&T research should be co-ordinated with the research and development being conducted in other countries. To, at this stage, allocate resources for further P&T research is also in line with the view that our generation should give future generations the best possible conditions to decide whether they want to choose P&T as a method for taking care of spent nuclear fuel, instead of direct disposal alone (in accordance with the KBS-3 method, for example).

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9 Nuclear Waste, Ethics and Responsibility for Future Generations

9.1 Introduction

The Post-War period features several examples of technological projects that have been the subject of debate and discussion, not only among politicians but also among the general public at large. The construction of the Öresund bridge between Sweden and Denmark was preceded by an extensive environmental debate. Railway construction, mobile telephone masts, wind power plants and genetic engineering have been questioned by the public and politicians. However, none of these discussions is comparable with the debate created by nuclear power and nuclear waste, which started in the early 1970's.

In 1976, the first conservative government after 40 years of social democratic rule came to power in Sweden. This was largely due to the nuclear power and nuclear waste issue. This very issue also led to the resignation of Prime Minister Thorbjörn Fälldin and his entire cabinet in 1978. Fälldin returned as prime minister after the 1979 election, but the issue had entered a new political phase prior to the referendum on nuclear power which was held in March 1980. The result of the referendum led to a decision by a large majority of the Swedish Riksdag (parliament) to set the deadline for the phase out of nuclear power no later than by 2010.

The Chernobyl accident in Russia in 1986 took its toll, resulting in a number of fatalities, and also reopened old political wounds in Sweden. In spite of this, the Swedish phase-out decision was modified already in 1991 – partly as a result of the objective not to allow an increase of carbon dioxide emissions from fossil fuels to exceed the 1988 level. The energy policy guidelines that the Swedish Riksdag decided on in 1997 and 2002 no longer specify a deadline for the phase-out of nuclear power.

Since autumn 2002, negotiations have been in progress between the Swedish Government and the electricity producers with the aim of formulating an agreement to establish the conditions for an economically feasible continued operation and successive phase-out of nuclear power. One of the two reactors at Barsebäck was closed down in 1999, the second in 2005.

The conflict between different views on nuclear power and nuclear waste became less charged in the 1990's and, nowadays, there are other environmental issues that are considered to be considerably more serious than the nuclear waste issue. In spite of this situation, the issue of the disposal of spent nuclear fuel entails a major national decision concerning a technologically and morally complex, large-scale project. From this perspective, the nuclear waste issue can be viewed as having been put aside rather than forgotten.

This report focuses on nuclear waste and on the scientific conditions, consultation and decision-making processes that are necessary in order to find a safe solution for the disposal of the 200-300 tonnes of high-level, long-lived waste which are generated every year by the operation of Swedish nuclear power plants. Already there is a total of about 4,000 tonnes of such waste in storage at CLAB (Central Interim Storage Facility for Spent Nuclear Waste) at Simpevarp in Oskarshamn Municipality.

Most Swedes would probably accept the statement that the nuclear waste issue is not exclusively a technical and financial issue. The nuclear waste issue has other aspects besides rock types, groundwater flow, durability and welding methods. Nuclear energy and nuclear waste issues also entail moral and ethical judgments and priorities: Who is responsible for the safe disposal of high-level waste? Should we wait until new and improved technology is developed in the future? If not, which municipality and landowner should give up its land for a repository? What does our responsibility for future generations require of us?

How do we adopt a position with respect to these issues? The construction of a repository which must be robust for several hundred thousand years is an enormous technical undertaking. But what do we do in order to decide what is morally right or wrong with respect to the nuclear waste question? This is an entirely different type of question.

This chapter discusses some of the moral and ethical issues associated with nuclear waste. Clear boundaries must be drawn with respect to this discussion. We cannot avoid the fact that the nuclear waste issue is related to the further issue of nuclear power as a source of energy. However, this fact is not the focus of the discussion here. Regardless of whether one is for or against nuclear power, there are almost 4,000 tonnes of high-level waste in CLAB's storage pools on the Simpevarp peninsula, 40 kilometres (24.85 miles) northeast of Oskarshamn. In 2015 there will be 8,000. The hazardous radiation will only decay to non-hazardous levels in hundreds of thousands of years' time. What do we about this? What *should* we do if we wish to act in a morally and ethically responsible manner?

Who should be responsible for a more definitive solution to the nuclear waste issue? This question can be seen as a question of justice. Should the responsibility be borne by the generation that is now living or by a future generation? The responsibility for future generations also raises other questions. If we who are living in Sweden at this time decide to dispose of the waste, and if we allocate resources for disposal, organise and build a repository, deposit the waste and close the repository, to what extent should we take into consideration future generations' possible wishes to manage the waste in a better manner or to use it as a resource? This raises the question of retrievability.

To begin with, we shall describe and analyse a number of basic ethical concepts and principles. We shall then turn our attention to the question of what the principle of intergenerational justice, namely justice between current and future generations, means for the disposal issue. The discussion will lead to a discussion about the nuclear waste issue as an existential dilemma.

9.2 Ethics and Morality

Nowadays there is a great deal of talk about ethics and morality. Many people would like to see more ethics and morals in society. But what do they really want more of? Are they two different things? What are ethics? And what is morality?

In everyday speech, the words "ethics" and "morals" are used interchangeably, even though the terms have different etymological origins. The word "ethics" comes from the Greek "ethos", which means conduct. There is also a similar Greek word – "etos" – which means custom, tradition or habit. The word "morals" comes from the Latin adjective, "moralis", which means customary or habitual. The origins of these words do not provide any clear guidance apart from to indicate that they refer to human traditions and habits. In this broad sense, these words are not of any particular interest.

The term *morals* can be used in two main senses, which we refer to below as Morals 1 and Morals 2.

> ***Morals 1*** *refers to our conventional pattern of behaviour.*

Morals 1 are quite close to the original meaning of the word. However, according to current language usage, "morals" also means something else, namely, our perception of what is right and wrong. It is not only a question of our actual actions and our conventional patterns of behaviour.

> ***Morals 2*** *refers to our concrete convictions of what is right and wrong, of what is a good person, a good society or a good relationship to nature.*

What are *ethics* then? Ethics can be described as our reflections *on* morals, namely, the values that we have and the acts that we do. Why do I do as I do? Should I act otherwise? Why do I uphold these particular values about what is right and wrong? What is a good society? What is a good attitude to nature? Should I change my values?

Everyone has *morals 2*, namely convictions about what is right and wrong – regardless of whether or not we are aware of these perceptions. However, not everyone has ethics. Ethics entails taking a step backwards and reflecting on one's moral values. Not all people have reflected on the content of their morals. Whether or not ethical reflection leads to improved morals 1 is a matter of debate. However, we can probably claim that there is no automatic relationship between ethics and morals 1. Ethics can often improve morals 1, although something more is required in order to be an honest and upright person apart from passing a basic course in philosophical ethics.

The concept of ethics can be summarised as follows:

> ***Ethics*** *refers to our reflection on the content of our own and other people's morals 1 or 2.*

In this sense, ethics is a subject that can be studied at university. Research has been conducted which has morals as its subject. Such research could be described as *the systematic and critical study of the values and principles involved in morals*.

Therefore, an ethicist does not develop *theory* about quarks, ecosystems and planets or about economics, consumption patterns and international relations. An ethicist develops theory about what is (or is assumed to be) right and wrong, good and bad, desirable and condemnable, just and unjust.

Most ethicists rely on the existence of some form of basic ethical principles in normative ethics. According to a simple model which is often used by Göran Hermerén (inspired by the

American medical ethicists, Tom L. Beauchamp and James F. Childress, in the book, *Principles of Biomedical Ethics*, 1979 and later editions), there are four basic ethical principles:

1. *The principal of respect for autonomy,* according to which, people themselves should be allowed to decide over events in their own lives, as long as this does not impinge on the autonomy, welfare or interests of others.
2. *The principle of beneficence,* according to which we should do good unto others, prevent harm and prevent or remove anything that is harmful for others.
3. *The principle af non-maleficence,* according to which we have a duty to not cause other people suffering or harm.
4. *The principle of justice,* according to which cases which are morally equivalent should be treated equally with respect to the distribution of benefits and burdens.

These principles ought to be generally accepted, although disagreement can arise when they refer to specific issues. People can also have different views regarding how to act when the different principles are in conflict with each other. The principles are nevertheless useful as a starting point for moral considerations, for example, in order to find an ethically acceptable solution to the disposal of nuclear waste from Swedish nuclear power plants.

It is reasonable for the first principle, respect for autonomy, to be ascribed not only to human beings who are alive at present but also to future generations. The second and third principles, beneficence and non-maleficence, mean that safety issues must be central to each argument. *Is it reasonable for us, the generation that is currently alive, to limit our safety and the safety of our children in order to allow future generations the opportunity to exercise the right to retrieve the nuclear waste and utilise it in a way that they consider best?*

The fourth principle is about justice. However, it does not only mean that equivalent cases should be treated or judged equally. It also has to do with how resources and responsibilities are to be distributed among human beings who are now alive and it has to do with the relationship between the generation that is currently alive and future generations.

These arguments are further developed later on in this chapter.

These principles largely have to do with how we should act towards other people. However, to a large extent, the principles can also be applied to our relationship with other living creatures. This question brings us to a topic that is called environmental ethics.

9.3 What Is Environmental Ethics?

If one can distinguish between morals and ethics in general, one can naturally also distinguish between environmental morals and ethics. Environmental morality is our actual moral behaviour and attitudes to nature and the environment whereas environmental ethics is the systematic processing and reflection about our relationship and attitudes to nature. Therefore, everyone has environmental morality, consciously or unconsciously, but not everyone has environmental ethics. Environmental ethics can more exactly be defined as follows:

> *Environmental ethics is the systematic and critical study of the value-based attitudes that – consciously or unconsciously – guide the way in which humans behave* ***towards nature*** *(with the aim of suggesting and vindicating the ethical principles that should guide humans in their relationship with the environment).*

In other words, the focus of ethical studies may vary:

- *Health care ethics* concerns the relationship between the care provider and the patient.

- *Business ethics* concerns the relationship between different companies and their customers/clients.
- *Environmental ethics* concerns the relationship between human being and the surrounding nature.

This means that every value system that systematically intends to guide us in our relationship with nature is a form of environmental ethics.

At this point, it is important to make a clarification. We should draw attention to the difference between *descriptive* and *normative* environmental ethics (or, more generally, between descriptive and normative ethics):

Descriptive environmental ethics attempts to *discover, describe and classify* the environmental values that people have. For example, the aim may be to (1) describe and classify the moral values that directly or indirectly guide environmental care and environmental policy and (2) analyse how people in general react to environmental policy measures (on the basis of their own basic values concerning how humans should act towards nature). It is important to emphasise that many other people apart from those engaged in the academic study of ethics are involved in descriptive ethics. Social science, humanities and ethical researchers conduct research in the area of descriptive ethics. We could talk about "value research" within the environmental area as a more general category of research. Without value research, it is difficult to conduct meaningful normative ethics. We need to ***acquire knowledge*** about the basic values that people have with respect to their relationship towards nature, especially regarding

- how these basic values are transferred, interpreted and perhaps even ignored by institutions and authorities,
- how these basic values are connected to actions and ways of life
- how people's moral values etc. can be influenced in a successful and acceptable manner.

Specifically, *ethicists* are not satisfied with simply describing people's basic values or attitudes to nature. They also wish to evaluate these values critically and constructively. Such a constructive and critical study of environmental issues can be called *normative ethics*.

The aim of *normative environmental ethics* is to *critically* and *constructively evaluate* the moral values that, directly or indirectly, determine environmental care and environmental policy and people's reactions to these values. Examples of normative environmental ethical questions include:

- Should we try to preserve species that are threatened with extinction and, if so, why and to what extent?
- Should we take into account future generations in connection with the use of non-renewable natural resources such as fossil fuels? Do we have the right to use up all of the oil reserves? If we have the right to do so, should future generations be compensated in some way?
- Can we behave towards other living creatures in any way we like? Or must we take them into consideration when we act?

9.4 Nuclear Power and Environmental Ethics

9.4.1 The Principle of Minimal Risk

A particularly important ethical issue relates to whether or not people or animals can be severely harmed by the some 8,000 tonnes of spent nuclear fuel[1] which is planned to be deposited in a repository somewhere in Sweden within the next 50 years. The ethical principle of not subjecting others to harm comes into play here. Bearing in mind the fact that it is difficult to

[1] According to information provided by the International Atomic Energy Agency, at the beginning of 2003, there were about 171,000 tonnes of spent nuclear fuel from nuclear power plants around the world which were stored in some form of interim storage facility. Of this amount, about 36,000 tonnes were in Western Europe and almost 28,000 tonnes were in Eastern Europe. By 2010, the total quantity of nuclear fuel in the world is expected to be about 340,000 tonnes.

completely exclude anyone from being subjected to harm, a precautionary principle has been sometimes applied. This principle can be interpreted as a variation of the principle of non-maleficence (see Section 2). The principle could be called the "principle of minimal risk" and formulated as follows:

> *We should not subject ourselves or others to any more than a minimal risk of harm (unless particularly good reasons exist).*

One difficulty of this principle is to determine what minimal risk is. In medical contexts, minimal risk has sometimes been defined as follows: "The probability and the size of physical or mental harm that is normally encountered in daily life" (*Xeno-transplantatio*n *Inquiry*, p. 291). The difficulty of risk assessments of nuclear waste storage is that we do not have complete and absolutely certain knowledge of what could happen with a deep repository located in Swedish bedrock. We know about certain risks, but a basic problem is the unknown risks, namely, we do not have – and neither do we expect to obtain – any certain knowledge of all of the conditions that can result in risk, for example, high-level waste leaching into the groundwater causing harm to humans and animals in 25,000 years' time.

Another difficulty with the principle of minimal risk is that risk must always be weighed against positive opportunities. If there are particularly large gains associated with certain measures, one may be morally entitled to accept certain risks – especially if the risk is voluntary and primarily relates to the person committing the act. However, if a risk is imposed upon others, a new moral problem arises which is of relevance for the nuclear waste issue. Through hazardous waste, certain risks are imposed on future generations. And the margins for allowable risk should be narrower for imposed risk than for self-chosen risk. Such an approach appears to be reasonable, especially bearing in mind the possibility that it is the present generation who will primarily reap the benefits of nuclear power and that this is not as obvious with respect to future generations. This brings us to the fourth basic ethical principle of justice.

Justice is not a simple concept. The following is an illustration of how difficult ethical questions can be when we start to analyse this concept and what it means for the handling of the nuclear waste issue.

9.4.2 Intragenerational Justice and/or Intergenerational Justice

It is necessary to distinguish between two types of issues relating to the concept of justice:

1. Justice within the generation which is currently alive (intragenerational justice)
2. Justice between the generation which is currently alive and future generations (intergenerational justice).

Intragenerational Justice

The first justice-related issue is the question of how the benefits and burdens of nuclear power – such as the disposal of high-level waste – should be distributed. Could Sweden hand over the responsibility of managing nuclear waste to another country? Or could another country allow us to manage their waste? One thing is clear. The Act on Nuclear Activities states that a licence may not be granted for the disposal of nuclear fuel from any other country than Sweden. Corresponding regulations also exist in other countries, for example, in France and Great Britain. An international nuclear waste convention *(Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management)* also exists according to which the contracting parties are "convinced that radioactive waste should … be disposed of in the State in which it was generated" and "[recognise] that any State has the right to ban import into its territory of foreign spent fuel and radioactive waste." Sweden ratified the convention in summer 1999 and the convention entered into force in June 2001. When information comes to light, in debates, that Sweden, through its membership in EU could be forced to receive foreign nuclear waste, the Swedish Government has in different contexts rejected such statements and has explained that Sweden will not receive foreign nuclear fuel for disposal in Sweden.

However, would it not be possible for Sweden to reach an agreement with another country whereby that country would manage our nuclear waste in exchange for reasonable payment? Such a view has been held previously in Sweden. In connection with the commissioning of the first commercial reactors in Sweden, plans existed to reprocess nuclear fuel and deposit the waste in foreign facilities. These plans were abandoned for the reason that plutonium from reprocessed Swedish nuclear fuel could be used for nuclear weapons manufacturing. In 1977, the Stipulation Act was passed. The act prescribed that nuclear power producers, as an alternative to reprocessing, had to present a safe method for the handling and disposal of spent nuclear fuel in order to be able to start up new reactors. These producers initiated the nuclear fuel safety project (known as the KBS project) which, in 1983 proposed that the waste (the spent nuclear fuel) should be disposed of in Swedish crystalline bed-rock without reprocessing. The Stipulation Act was revoked in 1984, although the KBS project continued and is now at the heart of the plan for the disposal of spent nuclear fuel from Swedish nuclear power plants.

Intergenerational Justice

A discussion about intergenerational justice with specific reference to the nuclear waste issue could be conducted along the following lines.

The justice principle means that cases which are similar in morally relevant respects should also be treated and evaluated on an equitable basis with respect to the distribution of benefits and burdens. An example of the application of this principle is the distribution of benefits and burdens between men and women in society. As with race and ethnicity, gender is an unfounded basis for justifying discriminatory treatment, for example, different salaries between men and women. On the other hand, length of education or job responsibility could justify a difference in salary between different people. Consequently, salary differences are not considered to be an injustice in itself, even if the differences are sometimes so large that, for this reason, they seem unjust.

As far as nuclear power and nuclear waste is concerned, there is an important difference between the current generation and the future generation. It is mainly the current generation which has received the benefits from nuclear power in the form of electricity. Future generations can, to some extent, share these benefits through the research results and technological development that they can inherit from us. On the other hand, the Swedish nuclear power programme leaves behind a considerable burden which will exist for a very long time, namely about 8,000 tonnes of spent nuclear fuel which is life-threatening and hazardous to health unless it is managed and disposed of in a safe manner. Is it fair for the current generation to pass on the responsibility of dealing with this problem to the next generation?

The answer to this question is no. This answer can be justified both on legal and moral grounds. The legal justification is based on certain international agreements accepted by Sweden. In 1995, the IAEA adopted *The Basic Principles for Radioactive Waste Management*. According to Principle 5, the waste is to be managed in such a way "that will not impose undue burdens on future generations". Taking into account these principles, this consideration was formulated in the IAEA's Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management from 1997. According to Article 1, the objective of the Convention is

> (ii) to ensure that during all stages of spent fuel and radioactive waste management there are effective defences against potential hazards so that individuals, society and the environment are protected from harmful effects of ionising radiation, now and in the future, in such a way that the needs and aspirations of the present generation are met without compromising the ability of future generations to meet their needs and aspirations.

This statement embodies a certain type of ethical reasoning which has become common in international environmental contexts. The World Commission's famous definition of sustainable development in 1988 is a starting point

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (*Our Common Future,* 1987, p. 43)

If we accept the idea of sustainable development, we accept that we have a moral obligation to future generations of humanity. Resources and burdens should be distributed fairly between current and future generations. This means that the justice principle has been *extended in time* to include not only people who are currently alive but also future generations.

This means that, in our actions and our planning of society, we should take into moral consideration not only existing human beings (traditional anthropocentrism) but also future generations (intergenerational anthropocentrism). This means that we can talk about a new ethics. Never before have we considered that we could have a moral responsibility that lasts 5, 10, 15 or even more generations into the future. With respect to the nuclear waste issue, this responsibility is further extended to last for as long as the nuclear waste remains a health hazard, namely, about 100,000 years, in the case of spent nuclear fuel.

An important question for us to investigate is exactly what this responsibility or consideration entails, especially in situations where our interests can come into conflict with the interests that future generations may have. This "new" environmental ethical mindset (intergenerational anthropocentrism or the ethics of sustainable development) dominates the political sphere at home and abroad.

9.4.3 Ethics of Sustainable Development – Four Principles of Justice

What does intergenerational anthropocentrism, namely, the ethics of sustainable development, actually mean? This question is discussed below from the standpoint of four different principles of justice.

The Static Principle of Justice

The ethics of sustainable development can – first of all – be interpreted as a *static principle of justice* in the following sense:

> *We have a moral obligation to pass on to subsequent generations the same quantities and types of natural resources that our own generation inherited from previous generations.*

The static principle of justice would have far-reaching conesquences if it were applied in practice. It could quite simply entail a prohibition against all major intrusions into nature. Why should we accept such a principle? Certain natural resources can be recovered after use, for example, certain minerals in electronic equipment. Other natural resources cannot be recovered but are renewable, which means that they can be used but they are regenerated. The Brundtland Report also upholds this view:

> In general, renewable resources like forests and fish stocks need not be depleted provided the rate of use is within the limits of regeneration and natural growth.

Even before the work of the World Commission, this thought had been generalised and transformed into a normative principle in the *environmental protection* doctrine:

> Human beings must exploit nature, but when nature is exploited, it must continue to be exploited in such a way that the sustainability of the ecosystem is maintained. (*Exploitation and Usage of Natural Resources*, SOU 1983:56, p. 187)

An example can serve to illustrate why the static principle of justice should not be accepted. When we exploit a watercourse, we might develop a pumping system in order to use the water more efficiently. However, the watercourse is still there for others to use. Let us instead assume that we exploit the watercourse by draining it in order to use the land for cultivation. Are we not jeopardising the possibility of future generations to use the watercourse to satisfy their own needs? Of course we are. They can no longer use the watercourse because it no longer exists. However, the Brundtland Commission did not consider that we would be contravening our intergenerational obligations by acting in such a way:

> Every ecosystem everywhere cannot be preserved intact. A forest may be depleted in one part of a watershed and extended elsewhere, which is not a bad thing if the exploitation has been planned and the effects on soil erosion rates, water regimes, and genetic losses have been taken into account. In general, renewable resources like forests and fish stocks need not be depleted provided the rate of use is within the limits of regeneration and natural growth. (*Our Common Future*, 1987, p. 45).

Not only is the current generation considered to be entitled to consume natural products. They also have the right to change existing natural areas without neglecting their moral responsebility to future generations. Therefore, we do not need to live with a minimum impact on nature. Furthermore, we are entitled to consume non-renewable resources such as fossil fuels and minerals, even if we reduce the access of future generations to these products by doing so. However, the condition that must be met is that "the rate of depletion that the emphasis on recycling and economy of use should be calibrated to ensure that the [renewable resources do] not run out before acceptable substitutes are available … [So] few future options [should be foreclosed] as possible" (p. 46). Thus, intergenerational justice does not mean that the same type or quantity of natural resources should be distributed equitably among generations.

The Minimal Principle of Justice

Bearing in mind the environmental protection doctrine, the static principle of justice should be rejected as a reasonable principle in environmental ethics – and in the discussion on nuclear waste disposal. Instead, another basic principle should apply, namely the *minimal principle of justice*:

> *Intrusion into the natural order is a human right. However, we have a moral obligation to exploit or consume natural resources in such a way that we do not jeopardise future generations' possibilities for life.*

If we accept the minimal principle of justice as a reasonable principle in environmental ethics, it will have clear consequences for the nuclear waste issue. Thus, we are obliged to use nuclear power today in a manner that does not harm future generations – even if these generations are very distant. We cannot escape from our obligations just because they have to do with very long-term consequences of our actions. We can make a comparison with objects that are located at a great distance from each other in space. Let us assume that people on the other side of the globe are affected by environmental toxins that, via air or water, could spread to New Zealand or Tierra del Fuego in a short period of time. The spatial distance is not a morally relevant circumstance and cannot excuse indifference for the consequences of our actions. In the same way, we cannot make an exception to the principle of non-maleficence just because the people concerned are at a large temporal distance from our own generation.

The Strong and the Weak Principle of Justices

There is a spectrum of intergenerational principles of justice which form the basis of environmental ethics, with the static principle of justice at one extreme and the minimal principle of justice at the other. Between these two extremes, two other principles of justice can be identified which are interim positions. We shall refer to the first as *the strong principle of justice* and this can be formulated as follows:

> *We have an obligation to use or consume natural resources in such a way that subsequent generations can be expected to achieve a quality of life equivalent to ours.*

This is a demanding principle which would probably entail far-reaching changes in the present generation's consumption patterns and exploitation of nature. This principle can be compared with *a weak principle of justice* which could be formulated as follows:

> *We have a moral obligation to exploit natural resources in such a manner that not only the present generation but also future generations can satisfy their basic needs (i.e. needs for food and water, protection against weather and wind, and access to work, health care and education).*

Some of the advocates of sustainable development move between the weak and strong principles of justice in their arguments about our responsibility to future generations. One example of such ambiguity is to be found in Andrew Kadak's article "*An Intergenerational Approach to High-level Waste Disposal*" (1997).

To clarify the difference between the strong and weak principle of justice, it is worth studying Kadak's arguments more closely.

In the article, Kadak presents the ethical guidelines that a working group, of which he was a member, appointed by NAPA[2], considers should be the starting point for the management and disposal of nuclear waste products and other substances. He writes that

> the objective was that no generation should (needlessly), now or in the future, deprive its successors of the opportunity to enjoy a quality of life equivalent to its own (Kadak 1997, p. 50).

Six general principles of application are attached to this overall objective. Kadak formulates one of these principles as follows

> There is an obligation to protect future generations provided the interests of the present generations and its immediate offspring are not jeopardised (Kadak 1997, s. 50).

Kadak also claims that these principles mean that

> The priority for today is the present population, although considerations of future generations must be factored into present day decisions.

The problem with Kadak's argument is that, on one hand, he maintains that future generations are entitled to the same quality of life as we have, while, on the other hand, he also maintains that we should prioritise the interests of the current generation over those of future generations. These two statements are not easily reconciled. It can be argued that, in the first quotation, he seems to accept the strong principle of justice, but that, in the next two quoted sentences, he assumes the weak principle of justice *at best*. The weak principle of justice allows us to prioritise our own interests, regardless of whether they are basic or non-basic in nature, as along as we do not jeopardise the

[2] NAPA stands for National Academy of Public Administration and, according to Kadak, is "a nonprofit, nonpartisan organization chartered by the U.S. Congress to improve the effectiveness and performance of government at all levels" (Kadak 1997, p. 49)

possibility of future generations being able to satisfy their basic needs. However, this does not mean that we can prioritise all of our interests without further ado. According to the weak principle of justice, the basic needs of future generations take precedence over the current generation's interests, which extend beyond our basic need for work, food, energy, housing, health care and education. Only when our interests conflict with those of subsequent generations' non-basic interests, can we consistently prioritise our interests. Not even if we were satisfied with the weak principle of justice could we, like Kadak, claim that we have "an obligation to protect future generations provided the interests of the present and its immediate offspring are not jeopardised."

Kadak's ambiguous statements about the current generation's precedence are even more problematic if the strong principle of justice is advocated. According to the strong principle of justice, we have a moral obligation to exploit or consume natural resources in such a way that subsequent generations can be expected to achieve an equivalent quality of life to ours. This means that we cannot even assume that our non-basic needs will always take precedence over the non-basic needs of future generations. An example may help to clarify this argument. Assume that we put forward the view that immigrants living in Sweden are entitled to the same quality of life as native Swedes. We would then be inconsistent in our argument if, at the same time, when allocating various resources to satisfy the non-basic interests of these two groups, we always prioritise native Swedes. The same argument applies when discussing the distribution of resources between generations.

The conclusion of this argument is that it is important to separate the strong and the weak principle of justice. The strong principle of justice puts future generations in a much stronger position than the weak principle, since the strong principle not only assumes that future generations will have the same basic needs to be satisfied but will also be given the necessary conditions to achieve the same quality of life.

Summary of the Four Principles of Justice

The principles can – in a very simplified manner – be summarised as follows:

The static principle of justice:

We have a moral obligation to pass on to subsequent generations the same quantities and types of natural resources that our own generation inherited from previous generations.

The strong principle of justice:

We have an obligation to exploit or consume natural resources in such a way that subsequent generations can be expected to achieve an equivalent quality of life to ours.

The weak principle of justice:

We have a moral obligation to exploit natural resources in such a manner that not only the present generation but also future generations can satisfy their basic needs.

The minimal principle of justice:

Intrusion into the natural order is a human right. However, we have a moral obligation to exploit or consume natural resources in such a way that we do not jeopardise future generations' possibilities for life.

The strong and weak principles of justice occupy a sort of intermediate position between the static and minimal principles. This is illustrated in the figure below. It is based on a scale which deals with the consequences of the present generations' patterns of consumption and exploitation of natural resources. Certain principles of justice would – if applied consistently – result in radical changes in our consumption patterns and use of natural resources. Other principles of justice have more limited consequences. Based on an intuitive assessment, the static principle of justice has the most far-reaching consequences – and the minimal the least far-reaching consequences.

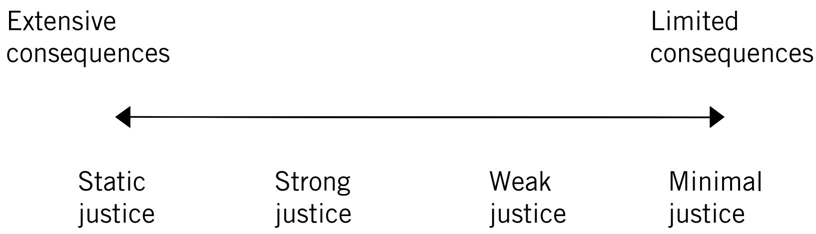

Figure 9.1. *Consequences for the current generation's consumption patterns and use of natural resources.*

9.5 The Nuclear Waste Issue as an Existential Dilemma

9.5.1 The Concept of "Diminishing Moral Responsibility"

In the previous section, the static principle of justice was rejected as a basis for our actions. Therefore, we have to, in some way, decide when a changeover from the strong or the weak principle of justice to the minimal principle of justice would be justified. This discussion can be conducted in connection with, for example, the assessment that has been made in KASAM's State-of-the-Art Report 1998. The report states the following concerning the basis for decision-making regarding the disposal of nuclear waste:

> The degree of credibility .... diminishes also over the course of time. Science too, has its limits of credibility. This means that our capacity to assume responsibility changes with time. *In other words, our moral responsibility diminishes on a sliding scale over the course of time*. (*Nuclear Waste State-of-the-Art Reports 1998*, KASAM 1998, p. 27).

This can be referred to as *the concept of diminishing moral responsibility*. What could this concept entail in practice for the question of the disposal of spent nuclear fuel from the Swedish nuclear power programme?

First of all, it must be emphasised that this is a question of attempting to make an assessment that does not have the exact nature of science. Our knowledge and our possibilities of making a claim about the long-term future, with any certainty are limited – not to mention the hundreds of thousands of years that spent nuclear fuel can jeopardise organic life. Of course, one possibility is to completely refrain from making assessments if we do not have an adequate basis to support them or reject them. The physical presence of just over 8,000 tonnes of spent and hazardous nuclear fuel from the Swedish nuclear power programme will force us, in spite of everything to think about and adopt a position with respect to these issues. Even if our responsibility for distant generations is more limited than for generations that are closer to ours, we cannot totally escape from our responsibility towards people who will live in our region in thousands or even hundreds of thousands of years' time. Without wishing to sound dramatic, it could be said that the nuclear waste issue raises a basic existential dilemma: moral responsibility forces us to adopt a position with respect to issues that we are not sufficiently equipped to answer. It is not only that we have inadequate knowledge about certain things, for example, when we can expect a new ice age or whether a more severe earthquake could destroy the repository. It is likely that a new ice age will occur in what is now known as Sweden within about 100,000 years' time and it is unlikely that a major earthquake will occur here. We can attempt to take this into account in our safety assessments but we must acknowledge that the decisions that we make on the basis of these and other assessments of probability will be decisions made under uncertainty (see SKN Report 45 *Uncertainty and Decisions*. A report from a seminar on decisions made under uncertainty and concerning the nuclear waste issue, 1991). However, uncertainty is more extensive than a lack of knowledge. Furthermore, it is the case that the most that will happen in the long term and that can also affect a robust final disposal system is uncertainty in a more radical sense; it is question of conditions and phenomena that we do not know that we do not know anything about.

And yet, we cannot relinquish our responsibility. Strictly speaking, this situation is not new. People have always been more or less aware of the limits of human knowledge. Religion has long been an important factor in controlling this uncertainty. Nowadays, research and science are the most powerful means of reducing the uncertainty that characterises human existence. However, if anyone believed that uncertainty can be completely eliminated, he or she has not reflected on how we should handle spent nuclear fuel from Swedish nuclear power plants in an ethically responsible manner.

We shall now attempt to clarify the concept of “diminishing moral responsibility”. Our main thesis it that we should have a more extensive duty towards the generations in our immediate future – and apply the strong principle of justice – and a more limited duty towards distant generations – and apply the weak principle of justice. But why should we, in the very long term, only have a duty to ensure that our current generation does not jeopardise future generations’ possibilities for life according to the principle of minimal justice?

Naturally, we cannot specify any sharp cut-off point for changing over from one principle of justice to another. However, it would still be desirable to, in some way at least give some indication of arguments that could lead to some sort of cut-off point. In order to arrive at a solution, we probably have to discuss what justifies distinguishing between immediate future generations and distant future generations. The justification is – to put it briefly – that when we consider the remote future, we lack the ability to assess or influence, in a reliable manner, the needs that these generations will have in terms of energy, transport, housing, education etc.

Perhaps we can obtain a certain guidance for this line of reasoning if we look back in time and ask the hypothetical question, “What ability did the Europeans of the Middle Ages to imagine the needs of our present generation?” Would the answer be any different if we asked the same question with respect to people living at the end of the 1800’s? It is clear that, in any case, people living in the 1800’s would have been able to make a far better assessment than people living in the 1500’s. If we are entitled to blame any of these generations for our current environmental situation, this entitlement would apply to a greater extent to people living in the 1800’s than to those living in the 1500’s. However, there are some important differences that exist between them and us. These differences may make our responsibility greater and may mean that it extends further into the future. One such difference is that we have certain ecological knowledge that they lacked. This primarily refers to three scientific insights, namely (A) that there is an interaction and a mutual dependency between human beings and other living creatures and (B) several of the natural resources that humans have access to are limited as well as (C) that there is a limit to the ecosystem’s ability to absorb humanity´s waste products. With the help of statistics and computers, we can also, in a better manner than they could, make forecasts of future population increases, desertification, ozone layer depletion, the availability of and extent of depletion of the earth’s non-renewable resources. Our possibility to assess the basic needs of future generations has been extended. However, with certain margins, we can hardly say anything about those needs, in 300 years’ time, that will require special collective efforts so that can be satisfied. After this time, it is difficult to know what will happen. However, one thing we do know for sure and that is that the nuclear waste from our nuclear power programme is still potentially hazardous – unless it has been stored under conditions that effectively isolate the waste from the natural ecological cycle that characterises the biosphere. We know that people can be harmed by nuclear waste hundreds of thousands of years in the future.

With various reservations, we can therefore, distinguish a rough cut-off point about 300 years into the future. With respect to the time after this point, we can only apply the *minimal* principle of justice (to not harm future generations' possibilities for life). Prior to this time, the *weak* principle of justice applies (future generations should be able to satisfy their basic needs). However, there appears to be another cut-off point, which can be established at about 150 years into the future. Up to this time, the *strong* principle of justice applies; we have a moral responsibility to ensure that the next 5 to 6 generations can achieve an equivalent quality of life compared with our own.

Why should we create such cut-off points? Are they not pure inventions? This is possible, but the following argument could also be put forward.

Let us assume that a generation is the same as the average time that exists between *the start of two consecutive generations*. Today, this time would correspond to about 30 years. 150 years corresponds to about 5 generations. If we are generation 1, our children are generation 2, our grandchildren are generation 3, our grandchildren's children 4 and our grandchildren's grandchildren generation 5. If we who belong to generation 1 test our feeling of affinity, we can still – if we stretch our imaginations – feel an affinity with our grandchildren's grandchildren. Quite spontaneously, it does not feel as though there is a distinct limit in my feelings of moral responsibility between these generations. However, after five generations it becomes more difficult. Some of the present generation will live long enough to see their grandchildren's grandchildren (generation 5) and they can possibly imagine generation 6, but beyond this it is hardly possible.

This line of reasoning is not only based on the extent to which we are capable of moral empathy. It is also based on what we can influence and what we cannot influence. It would seem that our primary relationships can hardly be influenced for more than 5 to 6 generations into the future. If we extend the circle to include secondary relationships, our local community and the nation, this time could possibly be extended. However, at some point in time – and, above, that point in time is assumed to be after about 300 years– our possibility of predicting and positively influencing development appears to be almost non-existent. On the other hand, we can cause considerable negative damage in the very long term through the imprudent disposal of spent nuclear fuel. There is an asymmetry between the relatively short future that we can influence positively and the very long future that we can influence negatively.

Therefore, we should examine the idea *that the strong principle of justice expresses our obligations to generations living up to about 150 years in the future. The weak principle of justice expresses our obligations from that time onwards and for up to about 150 years. After that time, the minimal principle of justice takes over and applies for the remaining time that we can assume that mankind will be able to live on earth.*

9.5.2 Three Time Periods – Three Principles of Justice

The concept of diminishing moral responsibility can be illustrated graphically. The figure below consists of three different timelines, one for each of the three principles of justice on which we have based our ethical model: The minimal, the weak and the strong principles of justice. It could be said that the principles are correlated with different timelines in a way that clarifies the idea of diminishing moral responsibility.

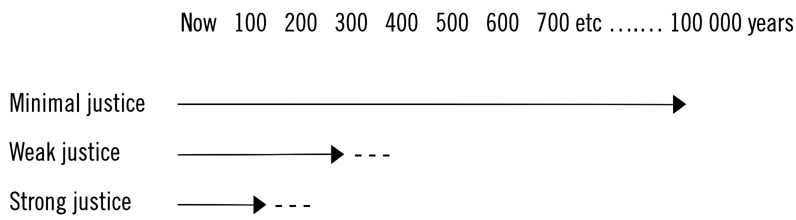

Figure 9.2. *Three timelines that define the main applications of the principles of justice in time.*

The dashed lines indicate that these are not sharp cut-off points. The extension of the strong and the weak principles of justice in time is dependent on whether or not it is reasonable to extend responsibility into the future. Responsibility is linked to ability. We cannot charge people with responsibility for something that they have not been able to influence. Or that they are not guilty of. This is a basic principle, not only in morality but also in ethics. Obligation presupposes ability.

However, there is another line of argument that could lend some support to the ranking that we have hinted at. This ranking means that (1) we have a basic obligation in the very long term not to do harm, (2) in the long term – namely up to about the year 2300 – we should satisfy the basic needs of future generations and (3) in the not so long term, namely up to the year 2150, we are also responsible for ensuring that they have quality of life that is equivalent to ours. We can refer to a type of similar line of reasoning in ethics for physicians. Even in the Hippocratic oath for physicians that was formulated a long time ago, there is a rule which is summed up in the Latin phrase "primum non nocere" (first do no harm). It is a doctor's first duty to do no harm; if a doctor cannot do otherwise, his or her duty is always to do no harm. It could be said that the next duty in the hierarchy is to satisfy the basic needs of patients. The patient has a disease for which there is no cure. However, the doctor can still ensure that the patient has his basic physical, mental, social needs satisfied. Uppermost in the hierarchy is the duty to give the patient the same quality of life as the doctor has himself/herself, namely to cure the patient. Thus, there is support, by analogy, for the ranking that we have made between the three principles of justice. This can be illustrated by the figure below.

Principles	Ethics for physicians	Intergenerational ethics
Not to harm or jeopardise life	Applies to everyone and always	From now – ∞
Satisfy basic needs	Applies to the incurably ill	From now – approx 2300
Give an equivalent possibility for life	Applies to the ill who are cured	From now – approx 2150

Figure 9.3. *Analogous ranking of obligations in ethics for physicians and ethics for the future.*

9.5.3 The Concept of the "Rolling Present"

Another important concept from *KASAM's State-of-the-Art Report 1998*, and which also recurs in *Responsibility, Justice and Credibility – Ethical Dilemmas Relating to Nuclear Waste*, 1999, p. 28), is the concept of the *"rolling present"*. The concept is related to a line of argument put forward by the American philosopher, John Rawls, in his classic book, *A Theory of Justice* (1971).

Rawls's Theory of a Social Contract under the "Veil of Ignorance"

Rawls's theory provides an answer to the question of why, in the first place, we have certain obligations to other people in general and towards future generations in particular. The answer is that ethical obligations are based on something that is similar to an agreement or contract between a group of people in a certain situation. What rights and obligations should we ascribe to people? Rawls answers this question as follows: the rights and obligations that it is in every individual's own interest to respect in *a hypothetical situation where all individuals are completely equal and their differences are hidden under a "veil of ignorance"*. In this situation, people are not only ignorant of the colour of their skin, ethnic identity, position in society etc. but also about the generation to which they belong. In such a situation, we would like to sign a contract that justice should prevail both within a generation and between generations. We do not only mean "justice" in the sense that we have discussed in this context, but also justice in terms of the allocation of human rights and justice with respect to social and economic benefits (even if Rawls accepts a certain inequality on this point – providing that the inequality benefits those least advantaged).

Why should what people accept as justice in such a fictitious world, under the "veil of ignorance", also count as justice for us in the real world? Rawls's answer to this question is not entirely unambiguous. We can distinguish between a pragmatic and a humanistic line of thought. The *pragmatic line of thought* means that it is better for everyone to live in a world where justice prevails. Everyone, even those who belong to the elite, benefits from a certain equality where no-one is essentially worse off than anyone else and where class differences are not too large. The difficulty of this argument is that it is only appears to be imprudent and unpractical to realise, for example, a fascist society. But is that not something completely different and worse, a crime against humanity? According to *the humanistic* *line of thought*, justice is simply an obligation because that which is of decisive importance for as humans is not that which distinguishes us from each other with respect to skin colour, upbringing, the lot that we have been given in life etc. What distinguishes us is our humanity; morality is our respect for all human beings and, this is the central aspect, an inherent part of our nature – and not temporary distributions of positions in the real world. It is this very aspect that Rawls wants to discern by referring to a fictitious situation "under the veil of ignorance". (In *A Theory of Justice*, Rawls is ambiguous but he seems to have developed a pragmatic interpretation later on).

In this way, a basis is created for certain principles of justice which agree with (but do not exhaust) the strong, weak and minimal principles of justice that we have described above.

The "Rolling Present"

Rawls has also provided an in-depth description of justice between generations. His views on this issue can clarify the concept of a "rolling present". What would we perceive as a desirable justice if we were in a situation where we did not know which generation we belonged to? Shrader-Frechette summarizes Rawls in the following way:

> … any reasonable person – who did not know to which generation, social class, intelligence bracket and so on he belongs – would accept the principle of equal apportionment of risks, resources, and goods as the distribution that is fair. (Shrader-Frechette 1993, pp. 191f. – see also Rawls 1971, pp. 284-293).

With respect to future generations, Rawls formulates a three-pronged task for the current generation. It should (1) preserve the gains that our culture and civilisation have made for posterity, (2) maintain our just institutions – and those institutions that maintain justice – intact, and (3) pass on to future generations a greater capital, in the form of more knowledge and better developed technology than we ourselves received from previous generations. This should compensate future generations for what we have consumed and pave the way for a better life in a society that is more just than today's. In brief: We should give future generations no less than we have received ourselves and preferably somewhat more at the same time that we prepare them for as much freedom of action as possible.

We should note an important nuance in this context. Rawls includes, but at the same time, expands the strong principle of justice as we have formulated it above. Not only do we have an obligation to exploit or consume natural resources in such a way that subsequent generations can be expected to achieve an equivalent quality of life to ours. According to Rawls, we also have an obligation to pass on a much larger capital than that which we have received from previous generations. It could be said that, with regard to this point, Rawls delivers something that could be a "moral overbid". Briefly, a distinction should be made between moral obligations and moral acts of supererogation. Let us take the following example: In certain situations, it may appear to be desirable to pass on to our children greater wealth and a better social situation than we ourselves received from a previous generation. If our parents were very poor and their social situation was difficult, such an objective could even be said to be very desirable. However, can we say that we have a moral obligation to pass on greater assets to children than those we received from our parents? Can it, in other words, be immoral to pass on approximately equivalent assets or slightly less? We can hardly say that this is the case. We have to distinguish between moral requirements and requirements that go beyond the call of duty, namely acts of supererogation.

This ethical theory can, in a natural way, be linked to the idea of a "rolling present". The basic concept of the "rolling present" is that the present and the future are interlinked through human beings and institutions, which carry obligations and possibilities for development from one generation to the next. Such a chain makes it possible to identify new uncertainties on the basis of new knowledge and to formulate improvements. The current generation has an obligation to provide future generations with resources to ensure that this chain of responsibility does not put unreasonable burdens on future generations. This is a consequence of a basic principle of responsibility that the producer of waste should also manage and dispose of the waste and, in different respects, ensure that it does not cause harm to other people.

According to the concept of the "rolling present", *each* generation has a duty to future generations. Each generation has a special duty to contribute to the generation that is next in line so that it can achieve an equivalent quality of life through knowledge, technical resources and cultural capital.

9.5.4 Applications

The final component in our ethical line of reasoning is at once the most difficult and the most controversial: *What concrete applications can be made from these ethical considerations with respect to the design of a repository for spent nuclear fuel from Swedish nuclear power plants?*

The Minimal Principle of Justice and Nuclear Waste

The principle of minimal justice applies for an unforeseeable period of time in the future and, quite simply, means that as long as living creatures exist on this plant, we have an obligation to not do anything that today that could jeopardise their life and health in the future. The consequences for the construction of a repository for spent nuclear fuel is both simple and difficult at the same time.

Therefore, on the basis of this principle, the specification for the repository should be completely clear: We must build a repository that can protection human beings and other living organisms for hundreds of thousands of years into the future – or for as long as we can anticipate that the waste is hazardous. There is also another requirement which a repository must fulfil, namely to prevent theft of spent nuclear fuel in the purpose of producing nuclear weapons. The implications of this requirement will, however, not be discussed in the present context.

We can probably claim that this future horizon will be broken at the time when a future ice age is expected to occur, perhaps in 20,000 years' time. During this period, the possibilities for life in Northern Europe will be limited for reasons that are easy to understand. Whether the waste will still be hazardous after a possible future ice age is a question that is related to theories about future climate evolution. If it is probable that one or several ice ages could occur during the period when the waste is still hazardous for human beings and other life, the minimal principle of justice requires that we should build a repository that can withstand these stresses and, in any case, not run the risk of being degraded to such an extent that leakage occurs. According to SKB's RD&D Programme 2001 (Chapter 10), climate evolution in a 100,000-year perspective is being studied in depth. KASAM also states in its review statement on the RD&D programme that the starting point of a safety assessment should be the period of time that the spent nuclear fuel represents a hazard. KASAM continues:

> The uncertainty in predictions and calculations can increase with time and this must be taken into account. However, to refrain from long-term assessments on account of the difficulty of making them can never be considered to be a reasonable level of ambition. (Nuclear Waste – Research and Technique Development, KASAM 2002:63, p. 32).

Such an approach can be justified by the principle of minimal justice, namely that we have a moral obligation to exploit and consume natural resources in such a way that we do not jeopardise future generations' possibilities for life. This principle can be clarified by placing it in relation to the concept of "diminishing moral responsibility" and the concept of the "rolling present".

The development in a 100,000-year perspective also requires another thing, namely that the repository should be constructed in a way that maintenance will not be required, even in such a long term perspective, in order for it to fulfil its purpose: i.e. to isolate the hazardous waste which in this specific case could be harmful to life and human beings. This approach is inherent in the "KASAM" principle which was formulated at the end of the 1980's: *A repository should be constructed so that it makes controls and corrective measures unnecessary, while at the same time not making controls and corrective measures impossible* (this principle is further developed in KASAM's report, *Nuclear Waste State-of-the-Art Reports 1998*, SOU 1998:68, p. 13).

We shall soon return to the requirement that the repository should not exclude maintenance. Let us first ask: Why should maintenance not be required? The answer is as follows: We cannot assume that people living 10,000 or 50,000 years after our time will have such technical skills that they would be capable of maintaining or repairing a leaking repository. Paradoxically, uncertainty concerning the future state of society, technology and knowledge clearly provides us with clear guidance for how we, today, must design a repository in a morally responsible manner. *It must be designed so that, without controls and corrective measures, it can protect the human beings who will live in its vicinity from about the year 2050 and a couple of hundred of thousand years in the future.*

The decisive question will be the following: Do we have the technical resources and the knowledge required to construct a facility that meets this requirement? In the opinion of many experts, the answer to this question is positive. The solution is the KBS-3 method. This means that the spent nuclear fuel will be encapsulated in canisters that will be deposited in boreholes at a depth of about 500 metres in the bedrock. The canisters will consist of iron with a copper sheath which will prevent water from coming into contact with the fuel. The canisters will then be surrounded by bentonite clay to protect them against bedrock movements and to limit groundwater movement around the canister. After the canisters have been placed in the rock, the repository will be sealed. The KBS-3 method is SKB's main alternative, although it has not yet been definitively approved by the regulatory authorities and the Swedish government.

In its review statement on SKB's RD&D Programme 1992, KASAM stated that the decisive safety issue is not the length of time it will take before the fuel canister is degraded, but the length of time that it will take for the toxic elements to be transported from the canister to the biosphere, which means that safety is ultimately determined by how the barrier system performs as an integrated whole. The most natural dispersion pathway is via the groundwater to the ground surface. However, toxins from the deposited waste can also reach the biosphere in the form of gases or through intentional or unintentional human intrusion.

It is impossible to calculate the probability of intentional human intrusion. To the extent that sufficient information is maintained and transferred in a reliable manner from generation to generation (in accordance with the "rolling present" concept), it could be said that the ultimate responsibility for the consequences of such an intrusion should rest with the party committing the intrusion and not with the party who has deposited the waste. Needless to say, a reliable transfer of information to reduce the risk of unintentional intrusion, is also morally required.

The critical question is perhaps whether we, at present, have sufficient knowledge and technical resources to prevent waterborne or gaseous leakage from the repository several hundreds of thousands of years into the future. Will the repository withstand the stresses of ice ages and earthquakes?

Let us assume that we will not have a reliable answer to this question in the application for the construction of a repository that SKB intends to submit to the Government in 2008. Should we nevertheless construct a facility that is the best that we can achieve at that time in order to avoid passing on the burden of finding a final disposal solution to future generations? One argument against doing so is that we shall be subjecting future generations to risk which could be avoided if we chose a solution which the American philosopher, Kristen Shrader-Frechette has called NMRS: "negotiated, monitored, retrievable storage facilities", namely, interim storage facilities where the waste can be monitored and from which it can be retrieved when we have more certain knowledge and better technology to construct a repository which will protect future generations for as long as waste can harm their life and health (see Shrader-Frechette 1993 and 1994). The principle of minimal justice requires that, with our technology, we do not jeopardise future generations' possibilities for life. First and foremost: Do no harm. This means that we should only construct a repository if we know that it is safe enough to protect future generations. Shrader-Frechette believes that if we cannot claim to know this, morality dictates that we should wait and see. In an article in *The Bulletin of the Atomic Scientists* 1994, she illustrates her arguments by referring to Tolkien's *Lord of the Rings*.

> Although he did not intend it, J.R.R. Tolkien, in The Lord of the Rings, suggested an answer of the riddle of nuclear waste. The ring gave mastery over every living creature. But because it was created by an evil power, it inevitably corrupted anyone who attempted to use it. How should the Hobbits, who held the ring, deal with it? Erestor articulated the dilemma: "There are but two courses, as Glorfindel already had declared: to hide the Ring forever; or to unmake it. But both are beyond our power. Who will read this riddle for us?"
>
> Humankind will eventually read the riddle. But at the moment, in the United States and elsewhere, its complexities are beyond us. In 100 years, that may not be the case (Shrader-Frechette 1994, p. 45).

It has been ten years since Shrader-Frechette's article was published. The KBS-3 method has been developed and it is possible that in Sweden we now have the knowledge and technology to give future generations the protection that we owe them. In that case, there is no ethical reason why we should wait and see – on the contrary.

Erestor talks about two possibilities: To hide the ring for ever – or to unmake the ring. In the case of nuclear waste, the latter alternative has a name, it is called transmutation. In her article from 1994, Shrader-Frechette writes that transmutation could be a useful method in about 100 years' time. In Chapter 8 of this report, such a possibility is examined in detail.

The Weak Principle of Justice and Nuclear Waste

The weak principle of justice means that we have a moral duty to use natural resources in such a way that future generations can satisfy their basic needs (namely, the need for food, water, energy, housing, health care and education). We have counted on this principle of justice applying for about 300 years into the future. If we construct a repository so that it does not harm living creatures in a 100,000-year perspective, we will also have ensured that, within about 300 years, people are not harmed by our nuclear waste. However, the weak principle of justice requires that we should do something *more* than not jeopardise their life and health – it requires something more active, namely, that we, the currently living generation, should take into account their basic needs. However, how can this principle guide us towards a solution of the final disposal question?

A repository is unlike most other facilities. It does not only exist to protect its contents from something outside (for example, theft for the purpose of producing nuclear weapons), but also to protect something outside from its contents. Its purpose is to keep something dangerous and hazardous isolated from life and human beings with the help of several solid barriers. Under certain conditions, these barriers can create a paradoxical problem, namely, if a future generation should find that it, in some way, it could benefit from the waste. Do we, who are currently alive and want to take responsibility for the nuclear waste in a repository, really have the right to prevent, in a more or less drastic way, future generations from gaining from the possible benefit of the waste? *Put in another way: Do we have an obligation to not unnecessarily limit the freedom of future generations (a) by refraining from closing the repository (b) by closing it but in different ways facilitating the retrieval of the waste (c) by closing it so that future retrieval is practically impossible?*

The question of retrievability has been a subject of different investigations and, in 1999, KASAM arranged a major symposium in co-operation with the IAEA (*International Atomic Energy Agency*). The papers from this conference have been published in a special report (*Retrievability of High Level Waste and Spent Nuclear Fuel*, IAEA-TECDOC-1187, 2000). The concluding discussion dealt with a basic dilemma. It seems as though there may be a direct conflict between two different requirements that we wish to place on a repository. One requirement is that it should be as safe as possible for future generations. This is a result of both the strong and the weak principle of justice. According to the weak principle of justice, we are obliged to respect and protect future generations' rights to satisfy their basic needs. The need for freedom of action to decide for oneself whether one wants to use or not use the deposited spent nuclear fuel for some purpose is undeniably a basic need. Can we uphold the weak principle of justice and future generations' possibility to retrieve the nuclear waste from the repository *at the same time that we also meet the requirements of the minimal principle of justice*, namely that we protect distant generations and do what we can to ensure that their lives and health are not jeopardised by the hazardous waste?

Perhaps there is no clear answer to this question. In that case, one possible approach is the following: If we cannot meet the requirement for future generations' freedom of action at the same time that we also minimise the risk of human beings in the distant future being subjected to life-threatening harm from our spent nuclear fuel, the minimal principle of justice – namely our duty to not jeopardise future generations' possibilities for life – should be given preference. In other words: The principle of not running the risk of subjecting future generations to harm carries more weight than our obligation to take into account the possibility that a not too distant generation would wish to gain access to the deposited nuclear waste and use it for some purpose. In this sense, we can also question the first stage of the "KASAM principle", namely that the repository should be constructed so that the retrieval of the deposited waste is possible. If this means that we, in some respect have to lower long-term safety, it is our obligation to put ”safety first”.

In addition to this, there is another risk of facilitating retrieval, namely that a not too distant generation – or perhaps another force – would wish to retrieve the waste in order to use it for destructive purposes.

The Strong Principle of Justice and Nuclear Waste

The strong principle of justice means – to formulate it negatively – that we who are currently alive do not have the right to implement measures that could result in future generations having a more limited quality of life than our own. The retrieval and final disposal of nuclear waste can be considered to be such a burden for future generations that it would be unjust of the current generation to not ensure that final disposal is achieved. According to the principle of minimal justice, we also have to construct the repository in such a way– during the time that the waste poses a hazard to life and health – that the hazard for future generations is minimised. The strong principle of justice goes one step further. It is our duty to ensure that human beings 5-6 generations removed can achieve an equivalent quality of life. This means that we may not pass on burdens to them which prevent them from satisfying their basic needs but also from enjoying life in the way that we have in our current situation. What consequences does this have for the final disposal of nuclear waste?

The answer is, *firstly*, that we cannot pass on the responsibility to a future generation and that we who have enjoyed the advantages of nuclear power must also assume the responsibility of constructing a safe, long-term repository for spent nuclear fuel (if we have the knowledge and technology to do so). If there are methods to conduct a project which fulfils such a specification, it is our duty to accept this moral challenge.

However – *secondly* – the strong principle of justice can also impose another obligation. It is our duty to transfer to the next generation resources which make it possible for that generation to improve the repository if necessary. The fundamental question will be: Is it probable that such a need will exist? Perhaps the probability is quite low. This does not prevent a minor but not completely negligible risk arising of such improvements of the repository becoming necessary in, for example 75-100 years' time, and of this necessity imposing a considerable burden on a future generation of achieving such an improvement. Under certain circumstances, this burden could be so great that it limits the possibility of our grandchildren's children from attaining a quality of life that is equivalent to ours. If we expect that our grandchildren's children may inherit many other environmental problems from us, and if we, furthermore, consider that there is a much greater risk of society's assets not being as comprehensive as today, the need for some sort of intergenerational insurance will not be an entirely irrelevant moral question. We can use the analogy of a shipping company, which is responsible for equipping its ferries and passenger ships with lifeboats or an airline which not only has a duty to equip its airplanes with life vests, emergency exits and other safety equipment. A shipping company or airline also has a duty to develop safety in the long term.

In the light of this, we could argue the following. The current generation has enjoyed the advantages of nuclear power. But have we paid the full price? To a certain extent, we can say that we have done this – since the 1980's, for each kilowatt hour of electricity, the electricity consumer has paid a few tenths of an öre[3] towards the management of nuclear waste. This amount also covers different protection and safety measures during actual repository construction as well as costs for an encapsulation plant and for the dismantling of nuclear power plants. We can anticipate to a far extent how these safety systems should be designed and what they should look like during the construction period and in connection with the deposition of the hazardous spent fuel. Once the fuel is in place, the risk of leakage from canisters and the repository must be minimised. The possibility for reparability can be partly anticipated and built into the final disposal system. However, there are risks that we cannot anticipate, but which subsequent generations could have greater knowledge of – and need to have access to greater resources in order to undertake corrective measures. One consequence of the strong principle of justice could be that we have a duty to "insure" future generations against risks that we cannot foresee and the burdens that necessary improvements of the repository could lead to. Such an insurance could take the form of a fund comprising sufficient financial resources for the next 150 years. Do we want to assume the burden and is it practically possible to accumulate financial resources in a fund on such a timescale?

This raises the topic of a "rolling present" in a very concrete manner. In order for such an insurance system to work, we have to achieve an effective transfer of knowledge, resources, values and institutions from one generation to the next, namely from us to our children and from us to them and to our grandchildren etc. Each generation must be given some form of freedom of action with respect to the direction and use of the accumulated resources. All of this could be contained in the concept of a

[3] 1 öre = SEK 0.01

"rolling present" (introduced in *Responsibility, Justice and Credibility – Ethical Dilemmas relating to Nuclear Waste*, 1999, p. 28). This concept raises a number of questions to which we cannot have a well-thought out answer in this context, such as the question of the design of a robust and sustainable insurance system – and whether such a system is also justifiable for other toxic substances that we who are living at present have dispersed into the environment and which imposes more or less far-reaching cleanup burdens on future generations.

However, there may be one or more concrete purposes for such a "final disposal insurance". According to the previously mentioned "KASAM principle", a repository should be designed so that it makes controls and corrective measures unnecessary and so that it does not make controls and corrective measures impossible. However, how can we at the same time satisfy the need for controls and the total isolation of the repository from the biosphere? Do controls not mean that we have to compromise on safety? If there is such a conflict, there could be grounds to postpone the final closure of the repository until a technical solution has been found to the control question which does not involve comprising long-term safety. This assumes that resources are available for technological development – and the obligations from the generation currently alive – which maximise the possibility to develop a method which will resolve the conflict between the requirement for control and safety.

9.6 Conclusions

The nuclear waste issue is not only a question of the technical construction of a final disposal. It is also a question of ethical and moral issues which concern our responsibility for future generations among other things. This chapter is an ethical reflection on this responsibility.

Spent nuclear fuel will be hazardous to human health and the environment for hundreds of thousands of years, in other words, until the radiation has decayed to a very low level.

- *The minimal principle of justice* requires that we do not jeopardise future generations' possibilities for life. This means that we – the generation which has enjoyed the advantages of nuclear power – have a moral obligation to create robust conditions for isolating the hazardous waste from the natural ecological cycle for a very long time. A repository for spent nuclear fuel must therefore be constructed in such a way that it does not require any maintenance or monitoring, even in the long term. At the same time, future generations must be given the possibility to monitor the repository and to improve the final disposal system. This principle is inherent in the "KASAM principle" which was formulated at the end of the 1980's: *A repository should be constructed so that it makes controls and corrective measures unnecessary, while at the same time not making controls and corrective measures impossible.* However, if the possibility of controls means that the long-term safety is less than if we refrain from such controls, we should prioritise long-term safety and refrain from controls. Safety first!
- *The weak principle of justice* states that we also have a responsibility and duty to use natural resources in such a way that future generations can satisfy their basic needs. This means that we should not unnecessarily prevent the freedom of action of future generations – and especially those living up to about 300 years into the future – from, for example, using the waste as a resource, namely, to enable retrieval. However, this only applies on condition that the long-term safety is not reduced. Our obligation to not risk subjecting future generations to damage is therefore greater than our obligation to take into account the possibility that a not too distant generation might wish to retrieve the waste for some purpose.

- *The strong principle of justice* entails being responsible for our actions so that subsequent generations – up to about 150 years into the future – can be expected to achieve an equivalent quality of life as we have, namely, so that they can enjoy life in the way that we have been able to in our current situation. The accumulation of the financial resources in the Nuclear Waste Fund, with the aim of ensuring that these financial resources are available for the final disposal of Swedish nuclear waste, contributes to our possibility of assuming this responsibility.

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Concluding Remarks

Every year, the operation of Swedish nuclear power plants generates considerable quantities of high-level, long-lived waste in the form of spent nuclear fuel and other radioactive waste. The possibility of safely handling and disposing of this hazardous waste is of decisive importance for human health and the environment, now and for a very long time in the future.

The vast majority of countries with nuclear power adopt a common approach to resolving nuclear waste issues. This common approach is manifested through the international *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management* that most countries have signed. Sweden was one of the first countries to sign the Convention. An international survey shows that Finland, Sweden and the USA have come the furthest in realizing the disposal of spent nuclear fuel, both with respect to the choice of technology and the siting process.

The construction of an encapsulation plant or a geological repository for spent nuclear fuel or other nuclear waste affects many people and institutions in society. The nuclear industry, the Government and the municipalities are three main actors. Individuals and NGOs are also highly involved in consultations, Environmental Impact Assessments (EIA), site investigations and in the choice of method and location for the possible siting of these facilities. A successful consultation and licensing process requires strong participation, particularly on the part of the municipalities concerned. The actors concerned must also be given adequate resources and opportunities to improve their knowledge.

The Swedish model for the consultation and licensing process on nuclear waste issues, with an extensive exchange of information at the feasibility study phase and with a more formal consultation process (in accordance with Chapter 6 of the Environmental Code) at a later stage, is characterized by openness, dialogue and democracy in the municipalities concerned. The Swedish Nuclear Fuel and Waste Management Company (SKB) has conducted early consultations with the local population and the county administrative boards in Uppsala and Kalmar counties and has subsequently started extended consultations including EIA with government authorities, municipalities, the general public and organizations that are assumed to be affected by disposal activities. The municipalities involved are Östhammar and Oskarshamn.

The choice of the best available technology and of a suitable site (which entails the least impact on human health and the environment), for the time horizon that is relevant for a repository for spent nuclear fuel, places great demands on the basis for decision-making for licensing under the Act on Nuclear Activities and the Environmental Code.

In-depth knowledge of the engineered and natural barriers is necessary for deep disposal in crystalline bedrock. The scientific basis for calculating the mechanical and chemical stability of the bedrock as well as the bedrock's permeability to radioactive substances for about 100,000 years into the future are important premises of safety assessment. Knowledge of ongoing bedrock deformation is a key issue in predicting stability. The methods for measuring and modelling bedrock movements must therefore be developed. This is also particularly important so that the groundwater conditions down to repository depth can be described and modelled. Through the thorough measurement of isotope ratios (natural and other isotopes), additional important information on the mechanisms for the transport of various elements from the deep repository can be obtained.

The need for method development also applies to the fabrication and control of the engineered barriers. In the case of the canister, acceptance criteria must be established and an analysis of the consequences of non-compliance with the criteria must be conducted. It is also important that these criteria should be verified using non-destructive testing methods and that a system for the quality assurance of canister fabrication should be formulated.

When making an overall assessment of the consequences of a waste facility for human health and the environment, it is important to be able to compare the risk from the radioactivity in the waste with the risk from the chemical toxicity of the waste. Furthermore, for a fair assessment, it is important to be able to make better comparisons between the toxicity of the nuclear waste and the toxicity of other types of waste than has so far been possible using the current classification system. A clear link between the classification and the requirements regarding the protection of human health will, hopefully, enhance public confidence in the waste management and disposal activities.

The Environmental Impact Statement (EIS), which must accompany an application for permission from the Government to construct a repository, must also describe alternative methods for managing the waste. Partitioning and transmutation has been mentioned in this context. In principle, this technology meets the general objectives for the management of the waste in general, namely, the use of the spent fuel as a resource (for further energy production) and a reduction in the toxicity and quantity of the waste.

However, in view of our current knowledge of this method, it is not acceptable to interrupt or delay the Swedish nuclear waste disposal programme on the basis that partitioning and transmutation is a possible alternative. On the other hand, this possible future alternative is a strong argument for a requirement that the repository should be designed so that the waste can be retrieved. According to the ethical principles that KASAM was involved in formulating, each generation should take care of its own waste and not force future generations to develop new technologies to solve the problems. Therefore, it is reasonable to set aside resources for continued research on partitioning and transmutation.

The nuclear waste issue is not solely a matter of resolving the technical design of a system for waste disposal. It also involves ethical and moral assessments concerning our responsibility for future generations and other considerations since the spent nuclear fuel is hazardous to human health and the environment for 100,000s of years.

Our generation, which has benefitted from nuclear power, has a moral obligation to create sustainable conditions for isolating the hazardous waste from the natural ecological cycle for this length of time.

Furthermore, we must not unnecessarily prevent the freedom of action of future generations, for example, with respect to using the waste as a resource. This means that the waste should be retrievable. However, this principle only applies on condition that long-term safety is not reduced. Our obligation to not run the risk of exposing future generations to harm therefore carries greater weight than our obligation to take into account the possibility that a generation in the not too distant future might wish to retrieve the waste for some reason.

We are also responsible for ensuring that future generations can achieve a similar quality of life to ours. The establishment of the Nuclear Waste Fund, which aims at ensuring that the financial resources exist for the handling and disposal of Swedish nuclear waste, helps to create the necessary conditions for us to assume this responsibility.