



STUDIECENTRUM VOOR ECONOMISCH EN SOCIAAL ONDERZOEK

FROM URANIUM TO ELECTRICITY  
DESCRIPTION OF MAJOR SIDE-EFFECTS\*

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Abstract

The generation of electricity on the basis of nuclear fissioning in a Light Water Reactor engenders various side-effects. The paper describes the major ones. The description follows the fuel cycle, meaning that the examination begins with the mining of coal and ends with the generation of electricity. Important side-effects are associated with fuel processing, nuclear plant operation, and waste management. More specific problems relating to uranium enrichment, routine radiation, operation and maintenance, reactor safety, thermal pollution, decommissioning, reprocessing, proliferation etc. are discussed. In the last section, we mention some mitigation possibilities, such as alternative fuel cycles. Special attention is paid to the state of the art of nuclear waste management. Completeness has not been aimed at.

## § 1. Introduction

In this paper we examine the most important side-effects of generating electricity from nuclear fissioning. The main part is devoted to the conventional nuclear fuel cycle, with electricity being generated in a Pressurized Water Reactor (PWR). The final paragraphs deal with new developments (amelioration of existing techniques, extensions of the conventional fuel cycles, and other fuel cycles).

Even a superficial examination of the problem learns that it would be heroic to assume that all side-effects are known, let alone quantifiable. Therefore, we do not aim at precise measurement, but rather at systematic description of side-effects. Our ultimate goal is a meaningful comparative evaluation of different electricity generating systems.

The structure of our analysis is based on the fuel cycle. We examine the major known side-effects, beginning with the mining of uranium and ending with its conversion to electricity.

Quantitative estimates always refer to a 1000 MWe PWR having a load-factor of 75 % (this is only a scaling convention). To account for uncertainties and variations, several hypotheses are put forward.

SECTION A : URANIUM MINING

§ 2. The standard practise to obtain uranium is to extract it from uranium ore containing limited portions of uranium. Currently, ore with a natural uranium content of 2000 ppm or less is being mined (1). (This means that the ore contains 0.2 % or less of uranium oxide,  $U_3O_8$ ). The amount of uranium ore required to fuel a 1000 MWe plant for a year not only depends upon the ore's uranium content, but also upon the efficiency of enrichment (see § 7). Using various assumptions about enrichment efficiency (cfr. table 4), we estimate that some 100,000 - 150,000 tons of uranium ore have to be mined each year (table 1).

TABLE 1 : Amount of uranium ore required annually (in  $10^3$  tons)

case n° * →	1	2	3	4**
uranium content of ore (ppm)				
↓				
2000	119	108	98	76
1900	125	113	104	80
1800	132	120	109	84
1700	140	127	116	89

\* the assumptions underlying the 4 cases are found in table 4.

\*\* a highly unlikely case

In the U.S., underground mines account for 70 % of the uranium production, while surface mines deliver 20 %. The remaining 10 % is obtained from second-hand sources such as tailings (2).

Uranium mining is not without dangers for miners (3). Inhalation of radioactive radon (and its daughter products) causes occupational diseases (and deaths), mainly pulmonary malignancies such as lung cancer. Since there are special hazards associated with mining operations, accidental injuries (and deaths) occur frequently. Estimates of occupational diseases and accidents have been compiled by COHEN & PRITCHARD (table 2). Figures vary widely, reflecting many uncertainties and variations.

TABLE 2 : Annual consequences of uranium mining to fuel a 1000 MWe plant (range of estimates from the literature)

Cancer (cases/deaths)	0.015 - 0.45
Accidental injuries	1 - 27
Accidental deaths	0.05 - 0.43

Source : COHEN & PRITCHARD (1980), 10,25

Other damages caused by uranium mining include : land disturbance, uncovered piles of radioactive waste, contamination of bodies of water, etc.

§ 3. Mined uranium is mixed with spoil material, mostly rocks. Dependent on the type of mine and the depth of the ore, the

amount of spoil material can range from 10 % to as much as 3000 % of the amount of ore mined (4). Usually, the spoil contains slight quantities of uranium (e.g. 0.005 %). Uncovered heaps of spoil, eventually enlarged with ore residues, continuously release radioactive radon (5). As a result, relatively insignificant amounts of radiation, but persisting over a very long time (100,000 years or more) may be observed. It is uncertain whether these small radiation doses harm human beings; if they do, total damage might be severe.

## SECTION B : URANIUM PROCESSING

- § 4. For use in a PWR, natural uranium ore has to be transformed into a fuel with a concentration of fissile isotopes sufficient to sustain a controllable chain reaction (6). Isotopes are termed "fissile" when they can be fissioned by a neutron of slow energy. The uranium-isotopes U-233 and U-235 are fissile; only U-235 is found in nature. Natural uranium typically contains 99.3 % of U-238 and 0.7 % of U-235.

To sustain a steady chain reaction ("criticality"), a PWR requires fuel with a 3 % concentration of U-235 ("enriched uranium"). The fissioning of this U-235 produces the heat that is the basis for electricity generation. During reactor operation, the available U-235 slowly "burns", i.e. converts to fission products while releasing enormous quantities of energy. Eventually, the reactor produces new fissile isotopes. This happens when a non-fissile isotope captures a neutron, decays, and converts to a fissile isotope; the non-fissile isotope is therefore called "fertile". In a PWR, U-238 is fertile since it can transform into the fissile Pu-239. The fissioning of the newly formed fissile isotopes produces additional heat.

"Breeder" are reactions that generate more new fissile material than the fissile material they consume. "Burners" are reactors that generate less new fissile material than the fissile material they consume. PWRs are burners; after operating for some time, the amount of fissile material has become too small to produce an efficient chain reaction. Therefore, one-third of the fuel is replaced annually.

In general the following steps are involved in fuel processing : milling of uranium ore to yellowcake, conversion to uranium hexafluoride, enrichment, oxide production, and fuel fabrication.

## § 5. Milling to yellowcake

Milling is the process whereby uranium oxide is extracted from the ore (7). The process consists of crushing, grinding and chemical refining. It results in a useful product named "yellowcake", containing 75 - 80 % of  $U_3O_8$ . To fuel a 1000 MWe plant, some 250 - 300 tons of yellowcake are produced, leaving more than 99 % of the ore as waste (table 3).

TABLE 3 : Annual requirements of uranium oxide and yellowcake (in tons)

case n° * →	1	2	3	4**
$U_3O_8$ required (tons) →	237	214.5	196	151
yellowcake required*** (tons) →	316	286	262	201

\* the assumptions underlying the 4 cases are found in table 4

\*\* highly unlikely case

\*\*\* assuming that 1 kg of yellowcake is needed to obtain  
0.75 kg of "pure"  $U_3O_8$

The spent ore, slightly radioactive, is dumped into settling ponds as a water solution. After evaporation, a grey, fine-grained sand known as "mill tailings" remains. If left uncovered, heaps of these tailings present hazards to health (8). Rain can leach out radium and other radioactive isotopes lea-



ding to contamination of drinking water. Wind can simply blow away radioactive dust. Radon gas, a decay product of U-238, continuously escapes from the tailings. Its daughters cause cancer if inhaled in the lungs.

The problem with mill tailings is not one of high radioactivity; it is rather a problem of low radioactivity combined with easy dispersion and huge quantities (g). The dangers of mill tailings have gone unnoticed for a long time; it is reported that up to 1966, mill tailings were used as fill for building foundations (10). Occupants sometimes received radiation doses equivalent to more than 500 X-rays per year.

#### § 6. Hexafluoride production (11)

To allow further processing, the present technology requires the conversion of yellowcake to uranium hexafluoride,  $UF_6$ .  $UF_6$  is a volatile material, turning into a gas at  $57^\circ C$ .

Two chemical processes are being used to produce  $UF_6$ : a dry one and a wet one. The dry process, known as hydrofluor process, generates solid wastes containing long-lived radionuclides. The wet process generates liquid wastes containing dissolved radioactive solids. Both kinds of waste are treated as low-level waste.

#### § 7. Enrichment (12)

Enrichment aims at increasing the concentration of U-235 in uranium. Different techniques based on the processing of  $UF_6$ -gas are used. All try to exploit the slightly heavier weight of U-238 (U-238 contains 3 more neutrons than U-235).

The gaseous diffusion process is the most widely used technique. It consists of diffusing  $UF_6$  through a porous barrier. Molecules of U-235 pass the barrier more rapidly than molecules of U-238, but nevertheless the procedure must be repeated more than 1000 times to obtain 3 % - enriched uranium. The gaseous diffusion process is very energy-consuming; ZACHAR asserts that the enrichment plants in Ohio, Kentucky and Tennessee consume about 3 % of America's total electricity production (13).

Centrifuge enrichment is said to consume less energy (energy consumption = 10 % of gaseous diffusion), mainly because the process has to be repeated only 12 times. But then again, "centrifuge enrichment may produce many times more waste than gaseous diffusion" (14). Other, less developed processes are aero-dynamic enrichment (with high energy requirements), and laser enrichment.

In every enrichment process, a trade-off has to be chosen between higher U-235 recovery (and hence higher costs), and lower U-235 recovery (and hence lower costs) (15). In general, the trade-off is function of both the costs of uranium and the costs of enrichment. For example, higher costs of uranium will probably lead to more enrichment; this means that less U-235 will be rejected in the enrichment tailings (the so-called "tail-losses"). Currently, enrichment tailings contain 0.2 - 0.3 % of U-235. Simple calculations learn that the concentration of U-235 in tailings substantially influences the amounts of  $UF_6$  required for enrichment (table 4).

TABLE 4 : Annual enrichment requirements

case n° →	1	2	3	4*
concentration of U-235 in tailings (%) →	0.3	0.25	0.2	0
amount of UF <sub>6</sub> , produced from yellowcake (tons) →	297	269	246	189
amount of enriched UF <sub>6</sub> produced (tons) →	44	44	44	44
amount of UF <sub>6</sub> rejected as tailings (tons) →	253	225	202	145
enrichment efficiency ** (%) →	63.5	70.1	76.5	100

\* highly unlikely case : assumes perfect separability of U-235 and U-238

\*\* as measured by "amount of U-235 in enriched UF<sub>6</sub>/total amount of U-235 in UF<sub>6</sub>"

## § 8. Fuel fabrication (16)

Finally, enriched uranium is converted to fuel. Uranium hexafluoride is transformed into solid uranium dioxide, UO<sub>2</sub> ("uranium metal") in the form of fuel pellets. These pellets are stacked in fuel rods, which are surrounded by a cladding usually made of zirconium alloy. Several fuel rods constitute a fuel assembly. The core of a reactor comprises more than 100 fuel assemblies. For example, the Biblis-B PWR-plant (1300 MWe)

in West-Germany comprises 193 fuel assemblies, while each assembly is a bundle of 236 fuel rods. The core of a typical 1000 MWe PWR contains 80 - 100 tons of enriched uranium. For our quantitative estimates, we have assumed that the core contains 99.9 tons of  $UO_2$ , of which 33.3 tons are annually replaced. 44 tons of enriched  $UF_6$  are needed to produce this 33.3 tons of  $UO_2$ .

SECTION C : TRANSPORT AND STORAGE

- § 9. The unavoidable presence of radioactivity complicates the transportation of uranium ore, yellowcake, hexafluoride and fuel. Although the radioactivity involved may be relatively small, exposure to it is in general not danger-free. However, the amounts to be transported are not very large. Massive transportation only takes place between mines and mills; but since mills are usually located in the near neighbourhood of mines, these transportation risks remain small.

Transportation accidents do occur. In the USA, there have been several accidents involving yellowcake and hexafluoride (17). In Europe, in 1967, 200 tons of  $U_3O_8$  "disappeared" while en route for France (18).

For the storage of radioactive materials, special measures must be taken to prevent the escape of radioactivity.

SECTION D. : CONVERSION TO ELECTRICITY§ 10. Construction (19)

In comparison to the construction of other types of power plant, the construction of a nuclear power plant requires substantially more labour and materials, and hence more time and money. As such, the occupational and public health risks associated with nuclear power plant construction are not abnormal. However, in relation to the risks from the other phases of the nuclear fuel cycle, the risks from plant construction may seem high. The risks would seem even higher if so-called "pre-construction" risks were included.

§ 11. Operation and maintenance

The public health aspects of reactor operation are discussed in § 12 (routine radiation) and § 13 - 14 (reactor safety). In this paragraph we deal with occupational risks.

Working conditions in nuclear plants are special due to the risk of radioactive contamination. Therefore, cancer is considered to be an occupational disease (20). Radiation exposure levels are in general thought to be quite low, in any case much lower than exposure levels in uranium mines and mills (21). However, some activities (repair and maintenance, refueling) seem more dangerous than others (22). Repair and maintenance operations sometimes have to be carried out in high-radiation areas. Refueling involves handling of "hot" burnt fuel containing enormous quantities of radioactive materials (e.g. Pu-239).

Estimates of occupational risks have been compiled by COHEN & PRITCHARD (table 5).

TABLE 5 : Annual occupational risks due to operation and maintenance of a 1000 MWe plant\* (range of estimates from the literature)

Accidental injuries	0.7 - 11.1
Accidental deaths	0.01 - 0.2
Cancer (cases/deaths)	0.024 - 0.21

\* including reprocessing

Source : COHEN & PRITCHARD (1980), 11, 27

It has been suggested that radiation levels will rise with increasing plant age, due to equipment activation and accumulated contamination (23). If this is true, contamination problems will become more acute in the future.

## § 12 Routine radiation

During normal operation, nuclear power reactors inevitably release tiny amounts of radioactive materials into the environment. Some of them result from fissioning, such as iodine (I-131), xenon (X-133) and krypton (Kr-85). These radioisotopes have short half-lives (Table 6), so their long-term impact (if any) must be limited. The most troublesome isotope seems to be I-131, since it accumulates in the thyroid gland where it can cause tumors (24). Increasing emissions of Kr-85 may effect the electrical characteristics of the atmosphere, thereby disturbing mechanisms regulating thunderstorms and rain activity (25). All in all, the effects of these released fission products appear to be extremely small. Emissions can be and have been limited in such a way that the maximum dose in the immediate vicinity of the plant is only a few percent of the background radiation (26).

Apart from fission products, radioisotopes from reactions involving hydrogen, oxygen and nitrogen are routinely released. More specific, radiocarbon (C-14) and tritium (H-3) are dumped into surrounding air and water, albeit in rather small amounts. Because of C-14's long half-life, its radiation will persist over a long period. If the present C-14 emissions were to have a small but adverse effect on human health, then the cumulative damage to health would be huge (27). Even in that case, the effect may remain unnoticed. Recently, several European nuclear plants have been "condemned" by the International Water Tribunal for their discharges of tritium (28).

TABLE 6 : Half-lives of selected radioisotopes

H-3	12.3 years
C-14	5570 years
Kr-85	10.8 years
I-131	8.05 days
Xe-133	5.28 days

Source : LIPSCHUTZ (1980), 178; TVER (1981), 269

### § 13. Reactor safety

In view of the extreme toxicity of some of the elements generated by fissioning (see also § 17), extensive safety measures have been designed to retain these elements within the plant. The principal area of concern is the reactor.

Several fission product barriers prevent radioactive materials from escaping the plant (29) :

- the crystal lattice of the fuel;
- the fuel-rod cladding;



- the reactor vessel, annex primary coolant loop; and
- the containment building.

Simultaneous malfunctioning of all these barriers would be a real disaster, since millions of curies of radioactivity would contaminate human beings and the environment.

Up to now, such an event has not occurred. But it can happen, and the conditions leading to its occurrence are identifiable.

The main problem is the cooling of the fuel (30). Even in the absence of a sustained chain reaction, heat production goes on. This heat comes from the radioactive decay of the fission products, and it is called "decay heat". Immediately after reactor shutdown, decay heat amounts to 240 MW of thermal power for a 1000 MWe PWR. Without removal of this heat, the fuel cladding would be damaged, and the core would melt through the reactor vessel, eventually breaching the containment. Therefore, safety measures are taken to prevent Loss-of-Coolant-Accidents (LOCAs) that would possibly lead to a "meltdown".

In general, three kinds of safety measures can be distinguished (31) :

- 1/ quality assurance of components and construction
- 2/ control and protective equipment
- 3/ engineered safeguards (safety systems).

To assure that the protective and safety systems keep functioning even if a component failed, the following design principles are applied :

- \* redundancy : for each safety function, more components or subsystems must be available than actually needed to perform the function;
- \* diversity : for each safety function, multiple equipment of different designs must be available;

- \* fail-safe : safety systems must go to a safe mode upon failure; and
- \* self-regulation : the system itself must recognize and indicate failures of components and subsystems.

The crucial question is whether nuclear power plants, with all of their carefully designed safety systems, are actually safe. In other words, what is the probability of a core meltdown, and what are its consequences? Risk assessment studies try to answer these questions. The basic study in this regard is the Reactor Safety Study - An assessment of accident risks in U.S. commercial nuclear power plants, published in 1975 by the Nuclear Regulatory Commission (32). A broadly analogous study, dealing with West-German commercial reactors, is the German Risk Study - A study of the risk due to accidents in nuclear power plants, issued in 1979 (33).

Basically, these studies have used "event tree" and "fault tree" techniques to define potential accident paths and to estimate their likelihood of occurrence. Since it is thought that only in case of a meltdown enough radioactivity would be released to cause a major hazard to the public, the main point of attention is the probability of a meltdown. To estimate the likely consequences of a meltdown, the probability of containment failure and the probability of various radioactivity dispersion patterns must be calculated.

The Reactor Safety Study and the German Risk Study both come to the conclusion that commercial nuclear reactors are extremely safe. The probability of a meltdown with serious health effects on the surrounding population is very low (Table 7).

The Rasmussen report even claimed that, for an individual, the change of dying from a nuclear reactor accident is as great as the change of being struck by a meteor.

TABLE 7 : Nuclear reactor safety (estimates)

Source →	Reactor Safety Study	German Risk Study
probability of melt-down (per reactor year) →	0.5 $10^{-4}$	1 $10^{-4}$
probability of prompt fatalities occurring due to meltdown (per reactor year) →	0.5 $10^{-8}$	0.5 $10^{-8}$
probability of "maximum credible accident" (per reactor year) →	0.5 $10^{-9}$	0.5 $10^{-10}$
some consequences of "maximum credible accident" →	3,300 prompt fatalities 45,000 latent cancer fatalities (30 year-period)	14,000 prompt fatalities 104,000 latent cancer fatalities

Source : NUCLEAR ENERGY POLICY STUDY GROUP (1977), chapter 7;  
GERMAN RISK STUDY (1981), chapter 8.

The Rasmussen report has been heavily criticized. Critics blaim it for its methodology, but even more frequently for its questionable assumptions. Some of the criticisms are :

- \* unknown or unexpected failure mechanisms cannot be included in the analysis (34)
- \* assigned probabilities are sometimes based on experience, sometimes on judgment (35)
- \* events are not necessarily independent where they have been assumed to be so (36)
- \* important effects have been omitted, e.g. the probability of a fire accident (37) (38).

As a result, risks may be seriously underestimated, by as much as a factor of 100; for example : the upper limit probability of meltdown has been estimated at  $0.5 \cdot 10^{-2}$  per reactor year (39).

The debate on the consequences of an eventual nuclear accident has mainly focused on public health risks. Recently however, more attention is being paid to financial risks. STARR & WHIPPLE contrast a utility's expected costs for outages of its nuclear plant with the expected public health risks related to the same outages (40). They conclude that the utility's costs are large compared to the public risks, suggesting that utility self-interest and public interest in safety are generally coincident. EVANS & HOPE even take into account the costs for other utilities : they assume that a serious accident in one plant will cause other plants of the same type to be (temporarily or permanently) shut-down for reassessment of safety standards (41). For widely used reactor types, these "indirect" costs are estimated to be many times greater than the "direct" costs (i.e. costs for the utility owning the deficient nuclear plant).

Finally, it must be mentioned that a large nuclear accident could set in motion a public reaction leading to forced shut-down of all reactors (42). The special attitude of the public towards nuclear risks has been frequently observed (43). This has influenced the nuclear safety debate, since arguments of "emotional" nature have been put forward by both advocates and opponents of nuclear power (44).

#### § 14. The Three Mile Island Accident

On March 28, 1979, a serious accident occurred in Unit 2 of the Three Mile Island nuclear power station (TMI-2) near Harrisburg, Pennsylvania. The core of the 1000 MWe PWR was

irreparably damaged. Ever since, views have been differing on the seriousness of the accident. Recent evidence seems to suggest that meltdown was just barely avoided (45).

What precisely happened ? (46) : The initiating event was a failure in the condensate polishers (47) of the secondary or "feedwater" system, leading to a total interruption of feedwater flow to the steam-generators. (This interruption was the effect of a "conscious" construction fault .) Automatically, the steam generators and the turbine tripped. At the same time, the emergency feedwater pumps were started. But the emergency feedwater was not delivered to the system, because a number of block valves that were required to be in "open" position, were actually "closed". (The closed position was only discovered 8 minutes after the initiating event .) Since the steam-generators did not any longer remove energy (heat) from the primary or "reactor coolant" system (RCS), temperature and pressure inside the RCS increased. Automatically, a relief valve (the pilot-operated relief valve (PORV) on top of the pressurizer) opened, soon thereafter followed by the insertion of all control and safety rods in the core ("scram"). Nuclear fissioning stopped, 8 seconds after the turbine trip.

Reactor coolant normally shrinks after a scram, due to lower temperatures in the core. To avoid excessive changes of volume, "letdown" and "makeup" of reactor coolant must be carefully monitored. 13 seconds after the initiating event, there were serious difficulties to increase makeup flow. (Problems with makeup and letdown pumps persisted for several hours.) At the same time, pressure in the RCS had lowered to a point at which the PORV is designed to close. A closing signal was given, but in reality the PORV did not close. In the control room, it was only indicated that the PORV had been ordered to close (not its actual position). The unnoticed open position of the PORV was the principal source for the accident to run out of control. On the one hand, it led to an unnoticed but persistent loss of coolant. The coolant first filled the

containment building, but after a while it was automatically pumped to an auxiliary building. From there, radioactive gases were "burped" to the environment through the ventilating system. This was the most important outlet for radioactivity during the accident. On the other hand, it led to erroneous readings of the conditions in the RCS. It was thought the RCS was completely filled when in fact it was continuously emptying. Subsequently, (a part of) the core became uncovered, leading to fuel cladding damage and escape of highly radioactive materials in the coolant. The very high temperatures then prevailing were also favorable for the zirconium alloy to react with water. In this way, substantial amounts of hydrogen were generated, forming a hydrogen bubble in the upper part of the reactor coolant loop. This bubble presented a serious obstacle to the reactivation of reactor coolant flow; when the operators had discovered the bubble, they feared it could explode (which was not true).

During the following days, control over reactor coolant was slowly regained, and further damage to the core could be avoided. Only on April 27, 1979, at 2.03 p.m., stable conditions were reached.

What then are the consequences of the TMI-2 accident ?

First, the core of TMI-2 has been damaged to such an extent that TMI-2 can never operate again; the financial costs of losing a good-as-new nuclear plant are enormous (48).

Second, the heavily contaminated reactor building must be cleaned up. This clean-up operation appears to be more difficult than originally thought (49). TMI-2 has for that matter been looked upon as a "laboratory" for decontamination and dismantling of large power reactors (50).

Third, people living in the neighbourhood of TMI-2 suffered economic losses, mainly due to evacuation (51). Long-term disruption of economic activity did not occur.

Fourth, the most significant effect on the population was the experience of evacuation in chaotic circumstances (52). Psychological distress was very high at the time of and shortly after the accident (53). A persisted anti-nuclear feeling contributes to the continuing inactivity of TMI-1 (54).

Fifth, the performance of officials was very confusing :  
" (...) no one in authority knew what the situation was, no one could know what the situation was because of inadequate information, and, still worse, no one knew what to do to protect the public." (55)

Fortunately, there is no evidence of any noticeable radioactive contamination (56).

Last, the accident revealed the importance of the "human factor" for nuclear safety. Human error significantly contributed to the TMI-2 accident (57). Since then, it has been "bon ton" to stress the importance of operator selection and training (58).

#### § 15. Thermal pollution (59)

A typical PWR converts about 32 % of produced heat to electricity. The remaining 68 % is dumped into the environment.

A PWR is usually equipped either with a once-through cooling system, or with a recirculating cooling system. In a once-through system, cooling water flows in and out of the plant only once. Evaporation takes place downstream or in the sea. In a recirculating system, cooling water is recycled through condensation/evaporation in a cooling tower.

Recirculating systems consume many times less water than once-through systems. However, recirculating systems require

huge cooling towers which are not very aesthetic. Large power stations combining several cooling towers ("heat islands") could have an appreciable micro-climatological effect.

## § 16. Decommissioning

It is generally estimated that a nuclear power plant has a useful life of 30 - 40 years of operation. Retired plants cannot simply be demolished : radiation from the reactor vessel and equipment is much too intense (60). The radiation problem has to be tackled in place.

Three procedures have been proposed for decontamination and, eventually, dismantling of nuclear facilities (61).

Mothballing consist of removing all fuel and radioactive fluids and wastes, and placing the plant in protective storage. Entombment is mothballing plus shipment of selected reactor components off-site, followed by sealing of all remaining highly radioactive components within a closed structure. Dismantling-removal involves removal of all radioactive materials present, including soil.

The technical, financial and health aspects of decommissioning are to a great extent unknown, since no large nuclear reactor has ever been decommissioned. It is thought that decommissioning will generate the following quantities of low-level radioactive wastes (62) :

- \* mothballing : 60 m<sup>3</sup>
- \* entombment : 2,000 m<sup>3</sup>
- \* dismantling-removal : 14,200 m<sup>3</sup>

The reactor site will perhaps be permanently closed to other uses (63). Last but not least, there is great uncertainty about the financial implications of decommissioning. Costs



for the complete dismantling of a 4 year old 20 MW BWR in Minnesota amounted to one quarter of original costs of construction (in real terms) (64). Recent dismantling of a small research reactor is said to have costed as much as its construction (65). There is little doubt that decommissioning costs for large reactors will be proportionately higher (66). An indication can be found in the clean-up operation of the Dresden-1 reactor (a 200 MW plant in Illinois, brought on line in 1980). In real terms, clean-up costs are estimated to attain three quarters of the plant's construction costs (67).

We have mentioned that TMI-2 is now a kind of laboratory for decontamination and decommissioning (§ 14). It must be understood, however, that the radiation levels inside TMI-2 are probably higher than those inside a reactor retired after 30 years of operation. Nevertheless, techniques and equipment will be used that are similar to those required for decommissioning a retired plant. Therefore, the clean-up of TMI-2 "(...) may well demonstrate whether or not decontamination and dismantling of a large power reactor is even practical" (68).

## § 17. Nuclear waste management

All the materials originally dug up at the uranium mine are ultimately rejected as radioactive waste somewhere in the nuclear fuel cycle (mines, mills, enrichment facilities, nuclear plants). By means of contamination, activation, etc. additional forms of radioactive waste are generated throughout the whole fuel cycle. The total amount of radioactive waste is therefore many times greater than the amount of uranium ore originally mined. For example, it is estimated that the production of 315 tons of yellowcake from uranium ore containing 0.1 % of  $U_3O_8$  generates the following quantities of

waste (69) :

- 350,000 tons of uranium ore waste
- 3,250 tons of lime (CaO)
- 1,450 tons of sulfuric acid ( $H_2SO_4$ )
- 725 tons of manganese dioxide ( $MnO_2$ )
- 100 tons of ammonia ( $NH_3$ )
- 77 tons of sulfur dioxide ( $SO_2$ )
- 50 -100 tons of kerosene, explosives, etc.
- 170,000 - 250,000 m<sup>3</sup> of polluted water.

But not only the amount of radioactive waste increases; its radioactive content also does. In this respect, the most troublesome forms of waste are spent reactor fuel and reprocessing wastes, since these are heavily contaminated with long-lived radioactive elements. For example, at the time of reactor shutdown, spent reactor fuel contains some 58 important radionuclides, among which 12 transuranic isotopes slowly decaying into other radioactive isotopes ("daughters") over several thousands of years (70). At the time of discharge, the annually discharged spent reactor fuel of a 1000 MWe plant generates  $5.4 \cdot 10^9$  curies of radioactivities and 45 MW of thermal power (71). If dispersed as fine particulates and inhaled, the Pu-239 contained in this spent fuel would be sufficient to cause fatal lung cancers in the entire U.S. population (72).

These few facts indicate key difficulties with (some forms of) nuclear waste : extreme toxicity, long half-lives (sometimes more than 100,000 years), and decay heat. Therefore, the only safe way to manage nuclear waste is to isolate it from the biosphere, for tens of thousands of years. In view of this long time-period, safekeeping should be independent of human action and control (73).

Nuclear waste can be classified according to origin, form, radioactive content, kind of radiation, etc. (74). The usual classification is based on radioactive content. For example, LIPSCHUTZ distinguishes (75) :

- \* low level wastes : average radioactive  $< 35$  curies/m<sup>3</sup>, and average transuranic radioactivity  $< 10 \cdot 10^{-9}$  curies/gram;
- \* transuranium-contaminated wastes : in principle low level wastes, but transuranic radioactivity  $> 10 \cdot 10^{-9}$  curies/gram;
- \* high-level wastes (76) : average radioactivity typically 10,000 to 100,000 curies/m<sup>3</sup>.

Current waste management techniques include :

- dumping on ocean floors, for low-level wastes (77); this practise is declining due to doubts about safety;
- shallow land burial, for low-level and transuranium-contaminated wastes (78); several U.S. disposal sites have released radioactivity into the environment due to "haphazard" waste management;
- on-site storage in pools, for spent reactor fuel (79), originally conceived for short-term storage only (1 - 4 years), on-site pools have now become longer-term storage facilities due to absence of large-scale reprocessing and ultimate disposal facilities;
- reprocessing, for spent reactor fuel (see § 18).

The results of these and other waste management techniques are not encouraging. Disposal of low-level and transuranium-contaminated wastes has not always been safe; disposal of high-level wastes is still being studied. Temporary storage of high-level waste is safe in on-site storage pools; other techniques have shown grave deficiencies (80). Proposals for final disposal of nuclear waste are discussed further on (§ 22).

## § 18. Reprocessing

Reprocessing is a chemical technique for the extraction of uranium and plutonium from spent reactor fuel (81). By means of the widely used "Purex" process, almost complete recovery of uranium and plutonium can be achieved (up to 99.5 %). In theory then, reprocessing offers two powerful advantages : on the one hand, it could lead to fuel savings; on the other hand, the amount of long-lived radionuclides in the wastes could be reduced.

The historical experience with (commercial) reprocessing of spent reactor fuel is disappointing (82). In the U.S., commercial reprocessing has been abandoned, and even indefinitely deferred after a presidential decision in April 1977. In Europe, plants have operated far below capacity. The reprocessing fiasco seems to be the outcome of failed promises highlighted by technical difficulties, higher than estimated costs, and waste problems. The danger of proliferation is an additional factor disadvantageous to widespread commercial reprocessing (83).

The claim that the amount of long-lived radioactivity in and even the volume of the waste would be reduced, cannot be maintained in face of the facts (84). Removal of uranium and plutonium indeed reduces the volume of previous high-level wastes, but creates new waste-streams too : emission of radioactive gases liberated from the fission products (especially Kr-85 and Cs-135) (85), formation of transuranium contaminated wastes (some 30 m<sup>3</sup> with an activity of 1.7 million curies per 1000 MWe reactor year), and formation of a mixed waste-stream containing fuel cladding, filters, tools, etc. Accidents in reprocessing plants and during transportation present new health hazards to the public.

Potential fuel-savings must also be questioned. Some estimate the plutonium losses of fuel commercially processed to date

between 4 and 6 % (86). Recycled uranium contains considerable quantities of U-236, which cannot be separated from U-235 by conventional enrichment technologies; the presence of this non-fissile U-236 makes recycled uranium a less desired fuel (87). Recycled plutonium includes the non-fissile isotope Pu-242, and is therefore less apt for use in LWRs (88). This means that recycled uranium and plutonium are really destined for use in breeder reactors - if, at least, enough breeder capacity will be built.

#### § 19. The proliferation danger and the terrorist menace

Nuclear fuel cycle equipment destined for the generation of electricity may eventually be used for weapons production. That is why some people fear that a spread of nuclear power capabilities over the world will lead to a (rapid) spread of nuclear weapons capabilities. This is the so-called "proliferation danger" (89). It highlights the narrow link between civilian and military use of nuclear power, embedded in the context of international politics and the arms race.

If a nation is to be successful in nuclear weapons development, it must have at its disposal (90) :

1. uranium
2. facilities to produce highly enriched uranium or plutonium
3. personnel and information to operate these facilities, and to design and fabricate weapons.

Several routes have been identified that lead from the availability of "civilian" nuclear equipment to the capability of nuclear weapons production (91). Enrichment and/or reprocessing facilities have crucial importance in all of these routes. The U.S. policy to defer commercial reprocessing at home and to install a moratorium on export of reprocessing

technology and equipment, is explicitly grounded on the proliferation danger (92).

Comparable to the proliferation danger is the "terrorist menace". Terrorists could try to assemble a nuclear explosive device on the basis of material stolen somewhere in the nuclear fuel cycle, or they could try to sabotage a nuclear facility with the result that massive amounts of radioactivity would be released (93). A terrorist act may have severe impacts, both physically and psychologically (94). The likelihood of nuclear terrorism can not be assessed; it is however almost certainly increased by expansion of enrichment and reprocessing facilities (95).

SECTION E : MITIGATION

§ 20. In general, three options are available to mitigate undesirable side-effects of generating electricity on the basis of a PWR-oriented nuclear fuel cycle.

The first option is to improve the working on the existing PWR-fuel cycle. The structure of the fuel cycle remains intact, but some activities are made safer, healthier, etc. An example would be : to take measure to prevent radioactive gases from escaping nuclear plants.

The second option is to extend the existing PWR-fuel cycle. New activities enlarge the conventional fuel cycle. An example would be : to introduce large-scale commercial re-processing combined with a breeder program.

The third option is to abandon (at least partially) the existing PWR-fuel cycle. Some activities are simply replaced by other ones. An example would be : to replace the PWR by the Heavy Water Reactor (HWR) fueled with natural uranium.

In the remaining paragraphs we discuss mitigation measures illustrating these three options :

option 1 : mining and milling (§ 21), waste management (§ 22)

option 2 : the breeder reactor (§ 23)

option 3 : other fuel cycles (§ 24).

Our discussion of mitigation measures is far from complete.

§ 21. Mitigation and mining and milling

To improve working conditions in mines and mills, at least three measures can be taken (96) :

- equipment of workers with closed-cycle breathing systems, to avoid exposure to dust concentrations;
- reduction of hours worked by each miner, to decrease exposure to dust concentrations;
- improvement of ventilation, to lower dust concentrations.

All proposed measures inevitably increase the costs of mining and milling, which is of course no incentive to rapid implementation. That is certainly the reason why it is often said that not much can be done to improve working conditions in mines and mills.

Measures to mitigate other damages from mining and milling include (97) :

- coverage of mine and mill tailings, to prevent the escape of radon gases;
- reclamation of surface-mined land.

§ 22. Mitigation and waste management (98)

Several technologies have been and are being proposed for the safe management of nuclear waste, especially high-level waste. These technologies deal with two important aspects : on the one hand, the physical form of the wastes, and on the other hand, the characteristics of the storage/disposal medium. The question is whether the proposed form + medium would provide safe storage/disposal.

The form of the waste influences its manipulability, at the same time being an additional barrier for radioactivity. In general, solid wastes packed into metal canisters are thought to be the most appropriate solution. This means that liquid wastes first have to be solidified. Various solidifi-



cation techniques have been developed :

- \* calcination : the waste is sprayed through an atomizer and dried; the result is a highly radioactive granular product;
- \* vitrification : the calcined waste is mixed with a borosilicate glass frit, melted and cast into a mold;
- \* incorporation into crystalline ceramics;
- \* incorporation into synthetic rock.

Every technique has its disadvantages; none of them has been applied on a large scale. In view of the many requirements, this comes as no surprise. For short-term and large-scale purposes, vitrification seems to be the best technology.

For a long time, stainless steel has been looked upon as the best material for metal canisters. However, it seems that corrosion would destroy steel canisters within a matter of a few decades. Therefore, research on canisters made of corrosion-resistant materials is being supported.

Appropriately packed, wastes can be put in storage or be disposed of. Storage is temporary, and it implies constant surveillance. Disposal is terminal, and the wastes are presumably unretrievable.

The development of new storage techniques is stimulated by the absence of viable safe disposal opportunities, the problems with existing short-term storage facilities, and the possibility that large-scale commercial reprocessing will ever start. Especially the problems with on-site spent fuel storage pools will be acute in the very near future. An alternative storage facility could be the proposed Away From Reactor (AFR) spent fuel storage pool, which is in fact an extremely large storage pool located off-site. The main objection to an AFR-facility is that transportation of high-level wastes would drastically increase.

The safe management of nuclear waste ultimately requires the development of disposal techniques capable of safely isolating wastes for tens of thousands of years. The proposed disposal techniques include underground, seabed, ice, and space disposal.

Underground disposal (or "geologic isolation") means that wastes are disposed of deep within the earth's crust. The crucial element in all geologic isolation proposals is the nature of the proposed disposal medium. The medium is required to be stable, meaning not subject either to groundwater intrusion or to seismic and tectonic forces for a few hundreds of thousands of years. Salt (bedded and domed), granite, basalt, shale, tuff, etc. have all been proposed as disposal media, with salt as the most promising. Nevertheless, after years of research a number of technical uncertainties about geologic isolation have remained. These uncertainties relate to :

- \* the effects upon the host medium caused by repository construction and burial of hot wastes;
- \* the mechanisms of groundwater flow into and radionuclide transport out of the repository;
- \* the geologic behaviour of the repository area over hundreds of thousands of years;
- \* the response of waste canisters to emplacement in particular geologic environments.

Most countries supporting a disposal research program have given top priority to geologic isolation research. In spite of that, nowhere a site for high-level waste disposal has been selected as yet (99), and it may take years or even decades before a satisfactory solution is found.

Seabed disposal means that waste is disposed of in subocean geologic formations. Three formations have been proposed : deep ocean trenches, deep ocean sediments, and subsediment bedrocks. Only subsediment bedrock is seriously investigated.

Research on seabed disposal is years behind compared to research on geologic isolation. Many uncertainties remain, but the major obstacle may well be international law.

Ice disposal means that waste is disposed of in the continental ice sheets. Three concepts have been proposed: "meltdown", "anchored emplacement", and "surface storage". Meltdown is based on the free melting of hot waste canisters, reaching bedrock in a period of 5 to 10 years. Anchored emplacement and surface storage would allow retrievability for several hundred years, until a slow meltdown process eventually starts. The uncertainties are great, and the major obstacle may again be international law.

The last and most fantastic proposal is space disposal, meaning that wastes are disposed of in the sun, or even out of the solar system. This would require an extensive space shuttle program, as well as widespread reprocessing to hold the volume of waste to manageable proportions. Costs would be very high, energy consumption enormous, depletion of the atmospheric ozone layer substantial, and the chance of failure with subsequent release of radioactivity not unexistent. Therefore, space disposal is not a promising proposal.

#### § 23. Mitigation and the breeder reactor (100)

As mentioned (§ 23), reprocessing offers - at least in theory - possibilities for fuel-savings and for the reduction of high-level waste volumes. One way to fuel-savings may be the reuse of recycled uranium and plutonium as mixed oxide fuel in a conventional PWR. Another way may be the use of recycled uranium and plutonium in a breeder reactor.

The type of breeder reactor that attracts most attention is the Liquid Metal Fast Breeder Reactor (LMFBR). In a LMFBR

most of the fissioning is caused by very energetic ("fast") neutrons, while liquid sodium (Na) acts as coolant. A LMFBR operates somewhat more complicated than a PWR; for example : there is one more coolant loop.

The development of the LMFBR should allow to kill two birds with one stone : power production and formation of new fissile material at the same time. Initially, the reactor is loaded with a mixture of plutonium (or enriched uranium) and unenriched uranium. The fissioning of plutonium (or enriched uranium) generates the heat necessary for power production ; the U-238 in unenriched uranium captures neutrons and converts to Pu-239. This new Pu-239 can be used for power production later. In theory, the amount of newly formed plutonium can exceed the amount of consumed plutonium by as much as 40 %.

The practical difficulties with (experimental) breeder reactors have been and are numerous. The complex technology and the extensive safety requirements have led to higher than expected costs, with the result that breeders are only built with government support. To some, the prospect of widespread plutonium transports between breeders and reprocessing facilities is alarming in view of the potential dangers. The development of a "plutonium economy" is also considered favourable to the proliferation of nuclear weapons. Breeding efficiency has not yet attained the 40 % put forward. These difficulties and the relative "abundance" of natural uranium have drastically slowed down the pace of breeder development.

#### § 24. Alternative nuclear fuel cycles (101)

The characteristics of a fuel cycle are mainly determined by the type of reactor used for electricity generation. For example : a HWR, fueled with natural uranium, eliminates the need for enrichment. Some reactor types are listed in Table 8.

TABLE 8 : SELECTED REACTOR TYPES

Reactor type ↓	Fuel ↓	Coolant ↓	Moderator ↓	Burner/ Breeder ↓
Pressurized Water Reactor (PWR)	3 % enriched U, recycled Pu	water	water	burner
Boiling Water Reactor (BWR)	3 % enriched U, recycled Pu	water	water	burner
Heavy Water Reactor (HWR)	natural U	heavy water	heavy water	burner
High Temperature Gas-Cooled Reactor (HTGR)	90 % enriched U, recycled U-233/Th-232	helium	graphite	burner
Advanced Gas-Cooled Reactor (AGR)	2.3 % enriched U	CO <sub>2</sub> -gas	graphite	burner
Liquid Metal Fast Breeder Reactor (LMFBR)	recycled Pu and U-238	liquid sodium	-----	breeder
Light-Water Breeder Reactor (LWBR)	recycled U-233 and Th-232	water	water	breeder
Gas-Cooled Fast Breeder Reactor (GCFBR)	recycled Pu and U-238	helium	-----	breeder

SOURCE : ENVIRONMENTAL RESOURCES LIMITED (1980), 97-99; NUCLEAR ENERGY POLICY STUDY GROUP (1977), 392-399

To date, the most widely used commercial reactor types are the PWR and the BWR, followed by the HWR (Canada) and the AGR (Britain). In comparison, the other reactor types are only alternatives on an experimental or even theoretical level. At the moment the range of commercial alternatives is thus limited.

Notes

- (1) HAEFELE (1981), 50 - 53
  - (2) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 399
  - (3) RAMSAY (1979), 37 - 39, 109 - 115; TUCKER (1979), 137 - 139
  - (4) BOER (1982), 41
  - (5) COHEN & PRITCHARD (1981), 19; RAMSAY (1979), 37 - 39
  - (6) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 389 - 405
  - (7) LIPSCHUTZ (1980), 35 - 36
  - (8) LIPSCHUTZ (1980), 135 - 138; SALZMAN (1979), 113 - 114
  - (9) LIPSCHUTZ (1980), 54
  - (10) LIPSCHUTZ (1980), 137
  - (11) LIPSCHUTZ (1980), 36
  - (12) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 365 - 376
  - (13) ZACHAR (1979), 54
  - (14) LIPSCHUTZ (1980), 36
  - (15) Laser enrichment may be the exception : it is claimed that it can separate uranium almost completely in one single step.
  - (16) GERMAN RISK STUDY (1981), 3.14 - 3.16; LIPSCHUTZ (1980), 36; ZACHAR (1979), 54
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- (17) REYNOLDS (1979), 94 - 109
- (18) ENVIRONMENTAL RESOURCES LIMITED (1980), 89
- (19) COHEN & PRITCHARD (1981), 9; NUCLEAR ENERGY POLICY STUDY GROUP (1977), 176
- (20) COHEN & PRITCHARD (1981), 21
- (21) RAMSAY (1979), 110 - 115
- (22) TUCKER (1979); 140 - 141; that is why in some countries temporary workers carry out these activities.
- (23) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 177
- (24) RAMSAY (1979), 35
- (25) RAMSAY (1979), 90 - 91
- (26) COHEN & PRITCHARD (1981), 12; RAMSAY (1979), 34
- (27) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 177; RAMSAY (1979), 38
- (28) SCHMIT & DEKKERS (1981), 107 - 108
- (29) GERMAN RISK STUDY (1981), 3.6 - 3.7
- (30) RAMSAY (1979), 47 - 48
- (31) GERMAN RISK STUDY (1981), 3.9 - 3.12
- (32) commonly referred to as the "Rasmussen Report"; for methodology and main conclusions : LIEBERMAN (1976), 247 - 270; WILSON & CROUCH (1982), 122 - 127



- (33) GERMAN RISK STUDY (1981)
  - (34) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 227
  - (35) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 227; RAMSAY (1979), 52
  - (36) LIEBERMAN (1976), 266; NUCLEAR ENERGY POLICY STUDY GROUP (1977), 227
  - (37) RAMSAY (1979), 52
  - (38) On March 22, 1975, a serious fire broke out at the Browns Ferry Plant in Alabama; COMEY (1979), 72 - 93
  - (39) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 229 - 232
  - (40) STARR & WHIPPLE (1982), 1 - 7
  - (41) EVANS & HOPE (1982), 295 - 304
  - (42) RAMSAY (1979), 53 - 54
  - (43) COHEN & PRITCHARD (1981), 29
  - (44) cfr. MARSHALL e.a. (1983); they think the public has "a distorted impression of the risks of nuclear power", and look for more appropriate ways to present the risks; trying to minimize the risks of nuclear power, they clearly "overact".
  - (45) Anon. (1984a), 98 - 100
  - (46) NUREG (1980), vol. 2, 309 - 340
  - (47) The condensate polishers clear the water from impurities.
  - (48) EVANS & HOPE estimate the loss at \$ 1 billion (1982 values).
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- (49) The operation is one year behind schedule; the costs are estimated at \$ 1 billion (1982 values); Anon. (1984b)
- (50) LIPSCHUTZ (1980), 53
- (51) Economic costs for households have been estimated at \$ 20 million (1979 values); NUREG (1980), vol. 2, 633 - 640
- (52) NUREG (1980), vol. 2, 644
- (53) This is the so-called "nuclear neurosis"; TVER (1981), 219
- (54) TMI-1 was not operating at the time of the accident; it has not been operating since. The economic losses of this shut-down are very high; EVANS & HOPE (1982)
- (55) WEISS (1979), 39
- (56) NUREG (1980), vol. 2, 643 - 644
- (57) NUREG (1980), vol. 1, 148
- (58) LILIENTHAL (1980), 51 - 58
- (59) COHEN & PRITCHARD (1981), 20; ENVIRONMENTAL RESOURCES LIMITED (1980), 79 - 80, 123 - 125; RAMSAY (1979), 92 - 94
- (60) RAMSAY (1979), 65 - 67
- (61) LIPSCHUTZ (1980), 50 - 52
- (62) LIPSCHUTZ (1980), 52
- (63) RAMSAY (1979), 65
- (64) C.S.E.N.E. (1981), 286
- (65) SALZMAN (1979), 119
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- (66) C.S.E.N.E. (1981), 286
- (67) LIPSCHUTZ (1980), 53
- (68) LIPSCHUTZ (1980), 53
- (69) BOER e.a. (1982), 46
- (70) LIPSCHUTZ (1980), 177 - 179
- (71) LIPSCHUTZ (1980), 38
- (72) LIPSCHUTZ (1980), 163
- (73) LIPSCHUTZ (1980), 55
- (74) BOER e.a.(1982), 55
- (75) LIPSCHUTZ (1980), 33 - 34, 211
- (76) In the U.S., only reprocessing wastes were originally defined as high-level wastes; in view of the absence of large-scale reprocessing, spent fuel has also come to be considered as high-level waste; LIPSCHUTZ (1980), 34
- (77) BOER e.a. (1982), 109 - 113; QUARTIER e.a. (1983)
- (78) LIPSCHUTZ (1980), 125 - 135; NUCLEAR ENERGY POLICY STUDY GROUP (1977), 252 - 253
- (79) LILIENTHAL (1980), 81 - 85; LIPSCHUTZ (1980), 46 - 50
- (80) LIPSCHUTZ (1980), 114 - 117
- (81) LIPSCHUTZ (1980), 44 - 46
- (82) BOER e.a. (1982), 74 - 87; NUCLEAR ENERGY POLICY STUDY GROUP (1977), 321 - 322

- (83) Of course, reprocessing for military purposes continues.
- (84) LIPSCHUTZ (1980), 61 - 62; NUCLEAR ENERGY POLICY STUDY GROUP (1977), 248
- (85) Referring to the Windscale plant, the C.S.E.N.E. has stated "The reprocessing of spent reactor fuel (...) is by far the largest radioactive polluter of the environment in Britain." C.S.E.N.E. (1981), 285; also : SCHMIT & DEKKERS (1983), 64 - 69, 111 - 112
- (86) C.S.E.N.E. (1981), 286
- (87) BOER e.a. (1982), 61
- (88) BOER e.a. (1982), 82
- (89) RAMSAY (1979), 68 - 85
- (90) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 277
- (91) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 279 - 281; HEISING (1982), 106
- (92) LILIENTHAL (1980), 14 - 15
- (93) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 301 - 315
- (94) RAMSAY (1979), 83
- (95) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 301 - 315; RAMSAY (1979), 83
- (96) LIPSCHUTZ (1980), 35; RAMSAY (1979), 113
- (97) RAMSAY (1979), passim
- (98) LIPSCHUTZ (1980), 55 - 111

- (99) West-Germany seems to have come very close to selecting the Assen salt bed as high-level waste repository; see Anon. (1984c)
- (100) NUCLEAR ENERGY POLICY STUDY GROUP (1977), 335 - 363; RAMSAY (1979), 40 - 44
- (101) ENVIRONMENTAL RESOURCES LIMITED (1980), 97 - 99; NUCLEAR ENERGY POLICY STUDY GROUP (1977), 392 - 397

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