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SWEDEN

THE LONG-TERM NUCLEAR EXPLOSIVES PREDICAMENT

THE FINAL DISPOSAL OF MILITARILY USABLE
FISSILE MATERIAL IN NUCLEAR WASTE FROM
NUCLEAR POWER AND FROM THE
ELIMINATION OF NUCLEAR WEAPONS

Johan Swahn

Technical Peace Research Group
Institute of Physical Resource Theory
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UTAN TVIVEL ÄR MAN INTE KLOK

Tage Danielsson
(1928-1985)

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ABSTRACT

It is possible that the long-term global energy future does not turn out to be a breeder-reactor-based plutonium economy, but that a sustainable energy future based on renewable energy sources develops instead, i.e., a post-nuclear world. The thesis is based on a scenario where this is the case. Then large amounts of fissile material, that would otherwise to be consumed in the plutonium economy, will have to be disposed of as long-lived nuclear waste. This material is usable for the construction of nuclear explosives and consists of weapons-grade uranium and weapons-grade plutonium from nuclear weapons dismantled as a result of reductions of the nuclear arsenals, and reactor-grade plutonium produced in civil nuclear reactors, but not recycled. Regarding the possibilities of using reactor-grade plutonium for the construction of nuclear explosives, it is found that reactor-grade plutonium is an entirely credible fissile material for nuclear explosives, but that the increased spontaneous fission neutron background inherent in such material does provide an incentive for a nuclear explosives program to produce weapons-grade plutonium. On the other hand, laser isotope separation technology can be used to convert reactor-grade plutonium into weapons-grade plutonium.

Present planning for the final disposal of spent nuclear reactor fuel that contains reactor-grade plutonium calls for the deposition of the material in mined geologic repositories. This disposal solution does, however, not make the fissile material “practicably irrecoverable” and safeguards would have to be put on the material for an indefinite time-period. Thus our generations, who utilize nuclear power, will leave a burden on future generations that do not. This is the long-term nuclear explosives predicament.

In this thesis the predicament is examined. A scenario is described where the

production of new military fissile material is halted and where civil nuclear power is phased out in a “no-new orders” case. It is found that approximately 1 100 tonnes of weapons-grade uranium, 233 tonnes of weapons-grade plutonium and 3 795 tonnes of reactor-grade plutonium has to be finally disposed of as nuclear waste, as the use of large-scale nuclear technology is phased out. This material could be used for the construction of over 1 million nuclear explosives and will be available for such purposes for a very long time. Reactor-grade plutonium is found to be easier to extract from spent nuclear fuel with time and some physical characteristics important for the construction of nuclear explosives are improved. However, the biggest problem, the large spontaneous neutron background, does not decrease.

Alternative methods for disposal of the fissile material that will avoid the long-term nuclear explosives predicament are examined. Among these methods are dilution, denaturing or transmutation of the fissile material and options for practicably irrecoverable disposal in deep boreholes, on the sea-bed, and in space. Weighing in costs, environmental safety and public acceptance it is found that the deep boreholes method for disposal should be the primary alternative to be examined further. This method, which may make the fissile material more difficult to retrieve than from a mined repository, can be combined with an effort to “forget” where the material was put. This would, however, be a reversal of the present considerations where an attempt is planned to transfer as much information about the nuclear waste as possible into the future.

Included in the thesis is also an evaluation of the possibilities of controlling the limited civil nuclear activities in a post-nuclear world. It is found that the opportunities for an effective safeguard regime are very favourable. Some surveillance technologies that might find widespread use in a post-nuclear world are described, including satellite surveillance.

In a review part of the thesis, methods for the production of fissile material usable for the construction of nuclear explosives are described; the technological basis for the construction of nuclear weapons is examined, including the possibilities for using reactor-grade plutonium produced in civil nuclear power reactors for such purposes; also the present planning for the disposal of spent fuel from civil nuclear power reactors and for the handling of the fissile material from dismantled nuclear warheads is described. The Swedish plan for the handling and disposal of spent nuclear fuel is selected as a reference example of a spent fuel disposal system and is described in detail.

Keywords: nuclear explosives, nuclear weapons, construction, destruction, high-level nuclear waste, spent nuclear fuel, disposal, long-term, ethics, Swedish, fissile material, plutonium, production, transmutation, nuclear fuel cycle, military, laser isotope separation, sustainable energy future, sustainability, plutonium economy

PREFACE

This thesis is the first presented within the research field of technical peace research at the Chalmers University of Technology. The research field was established in 1987, on a trial basis, under the auspices of the Technical Faculty at Chalmers.

The thesis is, of course, my personal responsibility, but it does owe its existence also to many persons who have directly or indirectly been supportive in the process of its creation. I would like to especially acknowledge the following individuals or groups:

- Victor Weisskopf, who led a seminar on the threat of the nuclear arms race at the 1982 CERN Summer School, and who awoke my interest in the subject.
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- Professor Karl-Erik Eriksson who made the original proposal that technical peace research should be carried out at Chalmers, and professor Tor Kihlman who helped realize the proposal.
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- Karl-Erik Eriksson, my supervisor, for the time and support he gave.
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- Ulf Heikki at Satellitbild for his helpfulness and kind hospitality.
- Apple Computer for bringing us System 7 and the Powerbook.
- And, all those others, none named, none forgotten, who supported me throughout the years with inspiration, help and advice.

For those readers that do not master the Swedish language, let me say a few words about the citation at the front of the thesis. The meaning of the quote is twofold. It can be translated as "Without scepticism, one is not wise", but also as "One is, without doubt, insane". Tage Danielsson was a brilliant humoristic humanist whose subtle but biting reflections ceased at a moment in history when perhaps they are needed most.

I want to thank my parents and family and friends for their support and finally, I want to extend my deep love and gratitude to my wife, Eva Eiderström, whose patience was unending, to my eldest son Linus who could understand and sometimes

accept that his father had a “book“ to write, and to my youngest son Hampus, who was steadfast company in the final stages of the writing.

Göteborg, April 12th, 1992,

Johan Swahn

COMMENTS TO THE SECOND PRINTING

Corrections of errors that I have found in the first printing have been made. The only correction that I feel important enough to mention specifically is the previously incorrect use of the fissile plutonium production instead of the total plutonium production in tables 5.5 and 5.7. This in turn effects the calculations of the annual and cumulative reactor-grade plutonium production in civil nuclear power reactors that are made in Chapter 5, and the calculation of the total number of nuclear explosives that can be constructed using this material made in Chapter 6. The results of these calculations are revised in this printing.

A recent important change in the organization of the Swedish system for nuclear waste management also deserves mentioning here. Since the completion of the thesis the decision has been taken by the Swedish Government to shut down the National Board for Spent Nuclear Fuel [Statens Kärnbränslenämnd], SKN, and to transfer most of its tasks to the Swedish Nuclear Power Inspectorate [Statens Kärnkraftsinspektion]. The important role SKN has played in the past in influencing the development of the Swedish programme for nuclear waste management and disposal is described in the thesis. What this recent decision means for the future planning for and review of the Swedish nuclear waste handling programme still remains to be seen.

Göteborg, June 8th, 1992,

Johan Swahn

COMMENTS TO THE THIRD PRINTING

This is the third printing of my Ph.D. thesis. Four years have gone since I wrote the thesis and the world and the knowledge we have about the world has changed much since then. Some of the material in the thesis now feels a little outdated, some is more relevant than ever. The only change that has been made in this printing is that a missing label has been added to figure 3.2.

Göteborg, April 22nd, 1996,

Johan Swahn

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1. INTRODUCTION

”Burdens on future generations shall be avoided.”

KBS-3, Volume I, General, p. 1:3.

”Burdens on future generations shall be avoided wherever possible.”

KBS-3, Summary Volume, p. 2.

The nuclear establishment¹, military and civil, that has developed during the last fifty years has produced large amounts of nuclear waste, much of it long-lived and highly radioactive. Much effort has been put into finding solutions of how to dispose of the long-lived radioactive high-level nuclear waste in a way that is environmentally secure in the long term, i.e., for a period of up to and over one million years into the future.

In this thesis, however, we will examine another long-term aspect of the nuclear waste handling problem, an aspect that has unfortunately, for several reasons, been largely ignored so far. The nuclear waste is not only radioactive. It also contains fissile material that is possible to use for the construction of nuclear explosives. This material presently exists in the form of reactor-grade plutonium in spent nuclear fuel from civil nuclear power reactors as well as in the form of weapons-grade plutonium and weapons-grade uranium, i.e., highly-enriched uranium², from dismantled nuclear warheads from the reductions of the global³ nuclear arsenals⁴.

¹. The word establishment is, in this thesis, used in its formal sense and there is no intention to suggest the negative connotations sometimes put on its usage. The word “complex” could equally well have been used, but, apart from the association, albeit very correct in this case, to complexity, it has also, in some people’s minds, an undertone in that the term is used in the phrase ”military industrial complex”.

In using the word establishment in singular the author would like to emphasize the connection, not seldom denied or at least underrated, between civil and military nuclear technology.

². In this thesis we will more often use the term weapons-grade uranium than the term highly-enriched uranium, even when we are discussing other use for such uranium than in nuclear explosives.

³. It is perhaps a little early to call the present nuclear disarmament, with large cuts in the nuclear arsenals of the United States and the former Soviet Union, global. The nuclear arsenals of these states do, however, make up approximately 97% of the nuclear weapons of the world. One can expect that reductions in these arsenals will, perhaps after some delay, cause changes on how other nuclear-weapon states view the necessity of keeping all their nuclear weapons.

We can also note here that we will throughout this thesis use the term former Soviet Union instead of the now established name Commonwealth of Independent States (CIS).

⁴. On the civil side, there also exists separated reactor-grade plutonium from reprocessing, both in stock-piles and in fresh mixed plutonium and uranium oxide (MOX) fuel. There is also MOX-grade plutonium in spent MOX fuel. In addition there exists plutonium in fast breeder reactor (FBR) cores. There is also fissile material in the spent fuel from the world’s civil nuclear research reactors. The reprocessing of spent fuel has also led to the production of high-level reprocessing wastes but this waste contains only minute amounts of fissile material. On the military side, there is also fissile material in stockpiles of weapons-grade material as well as in the used up cores from naval propulsion reactors and from tritium and plutonium production reactors. (cont.)

All this fissile material is now primarily destined to become nuclear waste. On the civil side, the previously ambitious plans for reprocessing the spent fuel from nuclear power reactors and for the “burning up” of the released reactor-grade plutonium in fast breeder reactors in a “plutonium economy” have been largely abandoned⁵. This means that direct disposal of spent fuel has become the predominant nuclear waste solution for high-level civil nuclear waste. On the military side, the large cut-down in the nuclear arsenals is presently releasing a large surplus of military fissile material, weapons-grade plutonium and weapons-grade uranium, that also has to be disposed of as long-lived nuclear waste⁶.

Present planning for the disposal of high-level nuclear waste calls for the construction of underground repositories where the waste can be left unsupervised for very long time periods without causing any environmental harm. The fissile material, produced by a few generations in our time, that is deposited in these repositories together with the other high-level nuclear waste, can be used for the construction of nuclear explosives by future generations. This will be true for hundreds of thousands of years into the future. This problem we have chosen to call the long-term nuclear explosives predicament. In this thesis this predicament is thoroughly analyzed and some solutions are suggested that may be used to minimize the long-term burden of the predicament for future generations. The long-term environmental safety and radiation protection problems relevant for the long-term disposal of high-level nuclear waste are not discussed in the thesis⁷.

Later in this thesis we will discuss how the predicament has previously been approached officially. But, already here we want to cite two statements from official documents that may be seen as presenting a commonly shared view of the problem by persons working with, and planning for, the disposal of high-level nuclear waste.

The first statement is from a draft of a recent document considering some basic criteria for disposal of high-level waste. The document strongly emphasizes radiation protection requirements for a repository but a remark is made in the introduction that there are also specific requirements for disposal of spent fuel that concern the aspects of non-proliferation of fissile material. It then devotes one paragraph out of one-hundred-and fifty-one to these requirements stating⁸:

All this additional fissile material, however, represents a relatively minor part, albeit contributing as a complicating factor, of the total nuclear high-level waste handling problem. In the thesis these aspects are covered but are not allowed to divert the attention from the main problem that is discussed.

⁵. The only country that is proceeding with its recycling plans as if nothing has happened is Japan. France, Britain and Germany are strongly pressed, primarily for economic reasons, to rethink their dedication to reprocessing and recycling. It is difficult to predict what is going to happen on this front in the former Soviet Union but, as a market economy thinking spreads also to the nuclear field, it is hard to believe that any priority will be given to plutonium reprocessing and recycling.

⁶. It can be noted that, as a first approximation, we here treat the fissile material from dismantled nuclear warheads as nuclear waste, even though there are possibilities for re-use of some of the material in the civil nuclear fuel cycle. If the material is not used in such a way it is nuclear waste. In addition, when the military material is used in the civil nuclear cycle, it becomes nuclear waste, albeit of a new type. Towards the end of this thesis we examine whether it actually may be advantageous not to re-use the military fissile material in the civil nuclear fuel cycle.

⁷. This is, of course, a problem that also has to be solved in a wholly satisfactory manner.

⁸. Nordic Radiation Protection and Nuclear Safety Authorities (1992, p. 28). See the reference list for a detailed description of the status of this document, which is still a draft.

“Protection against diversion of fissile materials for the production of nuclear weapons is accomplished by the safeguards system operated by the IAEA in collaboration with national authorities. In principle the safeguards system covers also disposal of high-level waste, but the surveillance has not yet been established. The safeguards surveillance during the disposal operations will probably be made as that of present nuclear fuel handling facilities. The retrieval of fissile material in a sealed repository is very difficult, thus it is questionable whether safeguards would be necessary in the post-closure period. Final decision on the need for safeguards surveillance should be made by the generations living during the closure of the repository and thereafter.”

The second statement is from an appendix of an official document that describes the fundamentals of nuclear waste handling. The appendix discusses the possibilities of using reactor-grade plutonium in spent civil nuclear reactor fuel for the construction of nuclear explosives. The document states⁹:

“Today the opinion that even plutonium of reactor quality is usable for the construction of [nuclear] devices can be considered to be generally accepted. The drawbacks are, however, large and there are fundamental limitations for the performance characteristics that can be achieved.”

One can note that the first sentence begins with the word “today”. It has, in fact, taken a very long time for this fundamental knowledge to be accepted, at all, within the civil nuclear establishment. To state that the acceptance of this “opinion” is general in this day is still, I think, too strong an assertion. But, hopefully it has been accepted by the persons who have taken the time to study the subject.

These two statements can thus be considered to represent a common view shared by most people who work with, and plan for, the disposal of high-level nuclear waste¹⁰. We will return to these statements later on in the thesis. Let us first give a brief description of the layout of the thesis.

⁹ KASAM (1986, pp. 128-9).

¹⁰ The second document later on states (KASAM (1986, p. 129):

“The analysis that has been done regarding the possibility that the final repository for spent fuel might become a “plutonium mine” shows that a country that wants to gain access to plutonium-239 for nuclear weapons chooses other methods for this, primarily the short-time irradiation of uranium in a nuclear reactor.”

This statement could, in principle, also be called a “common view” shared by most people who work with, and plan for, the disposal of high-level nuclear waste. However, it is probable that most of these people have not considered this aspect and thus it would be improper to call it a “common view”. It would, however, easily be accepted as common view if it were widely discussed.

This comment is, when used in the present tense, also accepted by the author of this thesis.

1.1 Presentation of the Thesis

The question of how to deal with the long-term disposal of nuclear waste, civil and military, is extremely complex. The subject has numerous dimensions; technical, environmental, military/security and economical as well as political, psychological and ethical. This thesis examines the production of fissile material that can be used for the construction of nuclear explosives and the possibilities for finding solutions for the final disposal of this material so that it does not become a long-term burden for future generations.

The thesis first discusses the following points:

- How is fissile material that can be used for the construction of nuclear explosives produced?
- How are nuclear explosives constructed? Special emphasis is placed on a discussion of how usable reactor-grade plutonium is for the construction of nuclear explosives.
- What are the present plans for the long-term disposal of fissile material usable in nuclear explosives? Special emphasis is given to the plans for final direct disposal of spent fuel from civil nuclear power reactors. The Swedish plans for such disposal are described in detail and are later in the thesis used as a “reference plan” for comparison with other possible disposal methods.

These three points form, in three chapters, a review part of the thesis. They are included to give a knowledge base within the fields of military and civil technology that is necessary for the subsequent analysis of the long-term nuclear explosives predicament and possible ways out of it. This analysis, which forms the major part of the thesis, includes the following points:

- An estimate is given of the quantities of fissile material usable for the construction of nuclear explosives that have been produced already as well as those that will be produced in the future. In order to obtain an estimate of the amounts of reactor-grade plutonium involved, a scenario for the future of civil nuclear power, based on a “no-new-orders” case, is constructed. This can be seen as an approach that gives a lower limit to the problem, but that also carries with it the imperative of a “post-nuclear world” as discussed later in this introduction.
- The predicament is described: how the amounts of fissile material change with time; the qualitative changes of the plutonium that take place over time and how these affect the usefulness of the plutonium for the construction of nuclear explosives; how the accessibility of the fissile material in a final spent fuel repository changes over time.
- The implications of the predicament for present disposal plans for the fissile material, especially for spent fuel from nuclear power reactors, is discussed. The plans for safeguards of final spent fuel repositories are critically examined. It is argued that some sort of safeguard surveillance will be needed for an indefinite period of time for a spent fuel repository of the type that is to be constructed in the “reference plan”.
- An attempt is made to examine alternative disposal methods that might not need

such indefinite surveillance and the feasibility of these methods are briefly compared with the “reference plan”.

- Some consideration is given to possibilities of hindering nuclear proliferation that could arise in a “post-nuclear world”. The possibility to use satellite surveillance is highlighted. An analysis of what can be detected in a military fissile material production complex using remote sensing imagery is presented as a case study.
- Finally, the main conclusions and recommendations of the thesis are summarized.

Before we proceed with the two main parts of the thesis there are three subjects that also need to be briefly discussed in order to give a framework for the further discussion. We would first like to examine the ethical dimension of the long-term handling of nuclear waste. We would then like to discuss the concept of sustainability and the question of how nuclear power would fit in a sustainable energy future with respect to natural resource use. Finally, we would like to examine the tendencies that exist today which indicate that the world might be approaching a “post-nuclear” era.

1.2 The Ethics of the Long-term Disposal of High-Level Nuclear Waste

The long-term disposal of high-level radioactive waste gives rise to a number of ethical questions. In recent years the ethics of the handling of radioactive waste has been quite heavily discussed in Sweden within the authorities and other groups responsible for or otherwise interested in the handling and final disposal of nuclear waste. Two main questions have been addressed. The first is how heavy a burden the present generations benefiting from the production of electricity from nuclear power, should be allowed to pass on to the future generations that might be affected by the wastes produced. The second is the question whether future generations should be able to influence the disposal solution that is the result of our choice of waste handling system, i.e., should we strive to make it as easy as possible for them to modify the system, if they find they are able to improve it. We shall here discuss these two questions in relation to how these two issues have been treated in Sweden¹¹.

Let us first return to the first of the two citations that were given in the beginning of this chapter: “Burdens on future generations shall be avoided”. The citation is from the Swedish KBS-3 report that describes a system for final direct disposal of spent nuclear fuel, a system that is still officially the Swedish “reference plan” for such disposal. In the report this principle is given as one of three general principles for the final storage of radioactive waste. The other principles are that “a very high level of safety is required, in both the short and long term” and that “it shall be possible to carry out the necessary measures with the highest possible degree

¹¹. For a general description of the Swedish system for the handling of spent nuclear fuel the reader is referred to Chapter 4.

of national independence”¹².

The KBS-3 method is, thus, based on the idea that a final nuclear waste repository should not place a burden on future generations. According to the official view in Sweden, it is our generation’s responsibility to find a solution to the problem of building nuclear waste repository which, once it is sealed, does not need any surveillance. The KBS-3 type of repository was designed with this goal in mind. This principle is also the aim of the Swedish financing act, ”Act on the financing of future costs for spent nuclear fuel, etc.” from 1981, i.e., that the economic costs of nuclear waste handling are to be borne by those who utilize electricity from nuclear power.

In Sweden the nuclear power reactor owners have the direct responsibility for the final disposal of the nuclear waste, and they have formed a daughter company, the Swedish Nuclear Fuel and Waste Management Company (SKB), to plan for and to manage such a disposal. The task to review the Swedish reactor owner’s research and development programmes on the management and disposal of spent fuel is carried out by a Swedish Government agency, the National Board for Spent Nuclear Fuel [Statens Kärnbränslenämnd] (SKN). In the mid-1980’s an authority called The Consultative Committee for Nuclear Waste Management [Samrådsnämnden för kärnavfallsfrågor (KASAM)], was formed as an advisory body to SKN¹³. One of KASAM’s tasks was to publish a yearly report entitled ”The State of Knowledge on the Nuclear Waste Front”¹⁴. In its first report from 1986, KASAM starts a discussion from an ethical perspective on the problem of final disposal of nuclear waste (KASAM 1986). The previously dominating view is here questioned. They write¹⁵:

“ ‘...we lack the fundamental knowledge to take responsibility for every imaginable consequence to future generations and the basis of their existence’, and that, according to our humanistic world-view, ‘it is of great worth that we guarantee coming generations the same right to integrity, ethical freedom and responsibility that we ourselves enjoy’.”

This means that considerations of the rights of future generations in relation to nuclear waste disposal is stressed. Therefore the disposal method must on one hand be chosen so that it can be left safely without surveillance in the long term. On the other hand if future generations want to, for example, increase the safety of the repository by surveillance or access, they should not be hindered by the technical design of the repository. In September 1987 KASAM and SKN co-sponsored a

¹². SKBF/KBS (1983, Volume I, General, p. 1:3). Already in the Summary Volume, however, this principle is weakened as the phrasing there is changed to ”Burdens on future generations shall be avoided wherever possible” SKBF/KBS (1983, Summary Volume, p. 2). It is unclear why there is a difference in wording between the volumes. The other two principles are identical. The difference exists both in the Swedish and the English versions of the document.

¹³. KASAM was in 1990 reorganized as a scientific council under the auspices of SKN called The National Council for Nuclear Waste [Statens råd för kärnavfallsfrågor]. The new council has, however, kept the old board’s acronym, i.e., KASAM.

¹⁴. Reports were published 1986, 1987 and 1989. The report is currently to be published every three years and the next report is due in 1992.

¹⁵. The quotation is from KASAM (1987, p. 90) which in turn cites the KASAM 1986 report (KASAM 1986, p. 12). The translation is from SKN (1988B, p. 13).

seminar in Stockholm on "Ethical Action in the Face of Uncertainty" where this new way of thinking was examined¹⁶. In the 1987 issue of its yearly report KASAM devoted a special chapter to this seminar and some of the more important points brought up at the seminar were presented (KASAM 1987¹⁷).

Two lines of reasoning were presented at the seminar in support of this change of attitude. According to the first one, it is natural to put two demands on a technical product that is meant to be in use for a longer period, namely that it is safe to operate and that it is repairable. The same can also be demanded from a final waste repository. Therefore it should be built so that coming generations will not be forced to protect themselves from it, but can repair any mistakes that we may have made while disposing of the waste. The second line of reasoning builds on the impossibility of predicting future advances in knowledge. On one hand, we can not guarantee that today's knowledge of how to best dispose of nuclear waste will exist for all time and therefore need to build a secure repository that does not need surveillance. On the other hand, future generations may have much better knowledge than we do and may want to improve on our construction. These points are summed up¹⁸:

"These lines of reasoning lead to a double conclusion: 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. In other words, our generation should not put entire responsibility for maintenance of repositories on coming generations; however, neither should we deny coming generations the possibility of taking control."

This has since become the mainstream thinking in Sweden on the ethics of disposal of nuclear waste and it is strongly represented at SKN. This change in view has several implications for the plans for finding a Swedish disposal method for spent nuclear fuel.

First, it brings up the question of whether repository should be sealed or not. The authority that will supervise the safety provisions in the licensing process is the Swedish Nuclear Power Inspectorate (SKI). To prepare the authority for this task, a five-year research project called Project-90 was started in 1986. The results of the project have been summarized in a report (SKI 1991). The project examined the long-term consequences of sealing the repository or leaving it unsealed and accessible. The conclusion in the report was that an unsealed repository could result in unacceptable environmental consequences. Bad near-field and geosphere conditions might impair the integrity of the canisters in an open repository. From a safety point of view, the report recommended that sealing should take place soon after disposal. The question of how it is to be sealed is more difficult. The most secure way of sealing the repository might make the repository less accessible than desired according to the second conclusion.

¹⁶. The proceedings have been published as SKN (1988A).

¹⁷. A translation of this chapter into English has been published as a separate report (SKN 1988B).

¹⁸. From KASAM (1987, p. 91) as translated in SKN (1988B, p. 15).

The second question is that of information transfer to future generations. If future generations are going to have the possibility of repairing or changing the repository, they must know where it is and what it contains. A special Nordic Nuclear Safety Research Program has been started to try to find the best methods for accomplishing such an information transfer (Jensen 1991).

The third question concerns a more near-term aspect. There is some concern on the part of SKN regarding how the schedule for the final disposal of spent fuel proposed by SKB, as described in Chapter 4, restricts the next few generations from influencing the choice of disposal method, i.e., that we proceed too fast in deciding exactly how the disposal is to be done. After all, the last nuclear waste produced in the Swedish nuclear reactors may not be put in a repository until the middle of the next century.

Let us examine how SKB and SKN view this issue¹⁹. For its planning SKB has used a set of guide-lines that it considers to apply to a Swedish nuclear waste management system²⁰. These guidelines are that:

- “1. The radioactive waste products shall be disposed of in Sweden.
2. The spent nuclear fuel shall be temporarily stored and finally disposed of without reprocessing.
3. Technical systems and facilities shall fulfil high standards of safety and radiation protection and satisfy the requirements of the Swedish authorities.
4. The system for waste management shall be designed so that requirements on the control of fissionable material can be fulfilled.
5. In all essential respects, the waste problem shall be solved by the generation that utilizes electricity production from the nuclear power stations.
6. A decision on the design of the final repository for spent nuclear fuel shall not be taken until around the year 2000 so that it can be based on thorough understanding²¹.
7. The necessary technical solutions for the disposal of Swedish wastes shall be developed within the country, at the same time as available foreign knowledge shall be gathered.
8. The efforts shall be guided by the regulatory authorities’ continuous review and assessment and directives issued by them.
9. The activities shall be conducted openly and with good public insight.”

SKN has, in a review, chosen to examine these guidelines²². First, it comments that although the guidelines have been formulated by SKB they can be said to have been sanctioned by tacit consent by most of the authorities that have commented on SKB’s work at various times. Second, it points out some requirements for a

¹⁹. This is discussed in a review made by SKN (SKN 1990B) of the SKB research and development plan presented in 1989 (SKB 1989A).

²⁰. (SKB 1989A, p. 11).

²¹. This is the official SKB translation. The SKB original text in Swedish talks about a ”brett kunskapsunderlag”, which rather means a ”broad knowledge base”.

²². SKN (1990B, pp. 1-3).

repository that it believes can not be questioned. These are that²³:

- “1. The method for final disposal shall fulfil standards of radiation protection and safe working conditions for those who work with the spent fuel and its storage during the construction, the operation and a during a possible surveillance period thereafter.
2. One should be able to judge if the repository can fulfil set standards for the future protection of people and their environment against radiation from the stored radioactive materials.
3. The security of the repository shall in the long run not be dependent on human surveillance or human measures.
4. The repository shall satisfy Swedish obligations to ratified international treaties, for example the Non-Proliferation Treaty.”

SKN also states that the final repository shall be cost effective, i.e., that the chosen solution shall fulfil these specifications without considerable extra costs for insignificant increases in performance characteristics.

After this “clarification” SKN picks out two of the SKB guidelines that it considers to be in need for further discussion. These are guidelines number six and five above, i.e., that ”a decision on the design of the final repository for spent nuclear fuel shall not be taken until around the year 2000 so that it can be based on thorough understanding” and that ”in all essential respects, the waste problem shall be solved by the generation that utilizes electricity production from the nuclear power stations”.

Regarding the first of these points, SKN has the opinion that it can be questioned whether coming generations are best served by a definite decision of how the nuclear waste is to be disposed of already in the year 2000. SKN sees the possibility of an alternative plan being made where a demonstration repository is constructed which is, for example, 5-10% of the size of a full scale repository. It considers that SKB should replace the full-scale repository with a demonstration facility in its plans. This is where the second point comes in. SKN sees a demonstration repository as a way for the present generation to take its responsibility for the nuclear waste by taking the first steps towards a possible and secure enough solution, while keeping the freedom of action for the next few generations to continue on the set path or to choose one that they find better.

One more comment can be made regarding the fifth SKB guideline that “in all essential respects, the waste problem shall be solved by the generation that utilizes electricity production from the nuclear power stations”. The guideline reminds us of the second of the two initial citations of this chapter, i.e., that ”burdens on future generations shall be avoided wherever possible”. This statement is from the Summary Volume of the Swedish KBS-3 report²⁴. Not surprisingly, the ethical standpoint is here modified. Burdens on future generations should be avoided, but

²³. This is a translation by the author of this thesis.

²⁴. SKBF/KBS (1983, Summary Volume, p. 2). See note 12 for a discussion of the wording of this citation as compared to the first one from the first volume of the same document (SKBF/KBS 1983, Volume I, General, p. 1:3)

not at any price. In the author's opinion the reason for this modification is that if the costs become too high, then the economical burden on nuclear power generation might make it uneconomical to continue electricity production. This is of, course, not acceptable to the nuclear industry, and the costs according to them have to have an upper limit. How high or low this limit is, and what burdens on future generation it entails is not an easy question to answer, especially if there are also profit margins for the utilities producing nuclear electricity to include in such calculations. However, this dilemma has to be openly discussed. When making the final choice of method for the disposal of long-lived high-level nuclear waste it has to be clearly stated what burdens the chosen method will or might cause to future generations and why these burdens are not considered important enough to justify a higher cost for a better solution. We return to this problem briefly in the concluding chapter.

There is one further ethical aspect that concerns the long-term disposal of nuclear waste that has to be discussed. In the KBS-3 report there is a discussion of the possibility that future generations intentionally intrude into the spent fuel repository to retrieve "useful material that it contains, i.e., the copper or the spent fuel" (SKBF/KBS 1983, pp. 21:6-7). In the Summary volume this matter is also discussed briefly. One states that (SKBF/KBS 1983, Summary Volume, p. 53):

"It must be assumed that future generations will bear the responsibility for their own conscious actions."

This is, in principle, of course, a very good ethical standpoint. However, when it comes to the long-term nuclear explosives predicament there are conflicts of interest that make it less attractive. It is possible that one country, in a future world that has no nuclear weapons, utilizes the fissile material in an old spent nuclear fuel repository within its borders to build up a large nuclear arsenal. The country might then, from a position of strength achieve a repressive world hegemony. Nuclear weapons might be used in order to achieve this aim. One might argue that we, the present generation, should include such a possibility in our considerations.

1.3 Nuclear Power in a Sustainable Energy Future

The question of what energy sources will be available for future generations after the world's fossil fuel resources have been exhausted has been discussed for a long time. One very common view in the 1960's, 1970's and early 1980's was that a fast breeder reactor based plutonium economy would be the solution, and that it would be introduced relatively soon²⁵. Such an energy solution would utilize the worlds

²⁵. As an example Vendryes (1977, p. 34) states:

"It is reasonable to expect that two pairs of fast-neutron plants will be initiated in France between 1980 and 1985, together with the Superphénix, about 8 000 megawatts of electric-generating capacity in service in the early 1990's. Commitments may grow to 2 000 megawatts per year after 1985, so that by the year 2000 fast-neutron plants may account for about a fourth of the installed capacity and a third of the total energy output of all nuclear plants in France."

The inevitability of a plutonium economy is still a very widespread conviction within the civil nuclear establishment, even though only a few might still believe that such a development is immediately

limited resources of natural uranium much more efficiently. All the reactor-grade plutonium produced in today's nuclear reactors as well as fissile material from nuclear disarmament, would be consumed in such an energy future. There would thus be no fissile material deposited in repositories, but only long-lived, environmentally hazardous, reprocessing high-level nuclear waste. There would thus in this energy future be no long-term nuclear explosives predicament in the nuclear waste. However, the fast breeder reactor nuclear fuel cycle relies on the reprocessing and transportation of large amounts of weapons-grade plutonium produced in the breeders, so such a world energy system would instead be a long-term nuclear explosives predicament itself.

The disposal of nuclear waste has to be planned for an extremely long time span. The possibilities for human societies to be maintained over long time are not at all trivial. What seems to be certain, is that to-day's dominant type of society, the industrial society, is far from sustainable. This society is largely based on one-way material flows which lead to the accumulation of unwanted substances in geophysical systems and the biosphere. We all know about the hazards imposed on life on Earth by this accumulation: global warming; depletion of the stratospheric ozone layer that protects us from UV-radiation; acid rain, destruction of forests and soils; spread of heavy metals and other toxic substances in waters and soils; eutrophication of lakes and coastal waters.

To be sustainable, the handling of energy and materials in a society must fit into the local, regional, or global natural cycles of materials on the Earth's surface. In the long run, the only flows that can be extensively used in a safe way, are the renewable flows based on solar radiation. This is what "Our Common Future" (WCED 1987) has to be based upon. The present industrial society is not sustainable in this sense.

Twenty years ago, in 1972, the UN Conference on the Human Environment was held in Stockholm. That conference can be seen as a starting point for international environmental efforts that, until now, have mainly tried to limit the harmful effects of mankind's influence in the environment, a policy of damage control. In early June of this year the UN Conference on Environment and Development will be held in Rio de Janeiro. For the first time, this "Earth Summit" will properly put the idea of sustainability and sustainable development on the agenda for international environmental policy. We may not see fast results but we can be certain of one thing; the environmental policy of damage control will in time be taken over by one of planning for sustainability. The present generation is finding it hard to change their way of living. Already the next will have to.

There are important signs that the development of renewable and sustainable energy sources has already proceeded so far that only institutional reasons, and the low price on fossil fuels, is preventing large-scale introduction of such technology²⁶. There is growing evidence that such technologies, together with more efficient use of

imminent. That such recycling is not economical at present is, however, not seen as a hindrance to such a development in the future.

²⁶. See, for example, Goldemberg et al. (1988), Brower (1990) and Holdren (1990) for a further discussion of these developments.

energy will allow the creation of a sustainable energy future in a sustainable world. There is thus a possible long-term alternative to the nuclear plutonium economy²⁷.

Internationally, the civil nuclear industry has so far only had a secondary role in the handling of materials in the industrial society. But, as information from the countries of Eastern Europe and the former Soviet Union has shown to us, this role is far from innocent²⁸. It is quite clear that a technology in need of so many protective measures and such an elaborate waste handling is not very neatly integrated into the cycles of Nature. Therefore, like combustion of fossil fuels and extensive use of a large variety of minerals, nuclear power is a technology that is not easily made consistent with the limits set by integration in the natural cycles.

Experience from uranium mining shows that the amounts of material to be handled are not small. In addition, uranium ore is definitely a finite resource, although it may, with present levels of uranium consumption, last for a few hundred years²⁹. The recycling of plutonium in breeder reactors would, as discussed above, considerably prolong the time that the uranium could be used as a fuel³⁰. However, there would still be large amounts of long-lived nuclear waste produced. It must be emphasized that sustainability in the case of waste handling is not a question of being able to find enough material or sites for waste disposal. In the term sustainability is included an effort to minimize waste production. In a sustainable energy future, any energy source that produces waste will be considered inferior to one that does not. In addition, there are large risks of nuclear proliferation inherent in a plutonium (and a thorium) economy. In their book *Energy for a Sustainable World*, Goldemberg et al. (1988, p. 51) state:

”Because of this proliferation risk inherent even in once-through fuel cycles, nuclear power should be regarded as an energy source of last resort, i.e., pursued only in circumstances where viable

²⁷. To integrate man-made systems into Nature in a sustainable way is, however, a technological challenge. There are, for example, problems that have to be solved that concern the impact of renewable energy sources on the environment. See, for example, OECD (1988).

²⁸. If one expands one's point of view to also encompass the military nuclear complexes, the problem is even more serious, and extends also to Western countries. The safety problems of the military nuclear reactors and the enormous costs for cleaning up military nuclear wastes in the United States as well as the French nuclear tests in the Pacific are examples of this. The problems of nuclear waste handling in the former Soviet Union have been described in an alarming report and article by Cochran & Norris (1991A, 1991B).

²⁹. In fact, Häfele (1990B) estimates that a nuclear power capacity of 400 GW_e, which is a little above the present capacity, will exhaust the currently estimated world supply in 100 years. For an extensive evaluation of available global uranium resources, see OECD/NEA/IEA (1989).

There are also very large amounts of uranium dissolved in the world's ocean but it seems improbable that this could be used as fuel for nuclear power plants at a price competitive in comparison to present and future renewable energy sources. This may actually be true also for mined uranium ore at an earlier point in time than a couple of hundred years from now. The uranium ore to be mined in the future will be of decreasing quality with resulting higher production costs per tonne uranium produced. In addition, if the cost of restoring the environment destroyed in the mining process were to be added to the production costs this is even more true.

³⁰. The same amount of natural uranium can be used to generate approximately 50-100 times as much nuclear electricity if plutonium is recycled in FBRs as if the uranium is used in a once-through fuel cycle.

The use of a thorium/²³³U breeder fuel cycle would make at least the fuel supply seem infinite. Waste handling and proliferation considerations would still apply.

alternatives do not exist.”³¹

Thus, our conclusion is that a society sustainable over a long time span, i.e., for thousands, tens of thousands and hundreds of thousands of years, is not a nuclear society. In addition, it appears as though there are only two long-term energy futures that could develop³². Either we will have a nuclear plutonium economy, albeit existing in a sustainable world with regard to other resources, or we will have a sustainable energy future in a sustainable world.

Which way the future global energy system develops has important implications for how we choose to dispose of our long-lived high-level nuclear waste. A nuclear plutonium economy will not leave any fissile fuel in final long-term high-level waste disposal repositories and we can use up all the fissile material, both civil and military, presently being stored awaiting final disposal. In a sustainable energy future based on renewable energy sources there will, however, be large amounts of fissile material to be disposed of, both civil and military. This difference is not so large when one has to develop a disposal method that is environmentally secure in the long term. It is fundamental if one has also to consider the long-term nuclear explosives predicament of the fissile material in the waste.

The conclusion that a society sustainable over a long time span is not a nuclear society is, in fact, consistent also with what can be observed in the short run. There are already several signs that we are, in not too distant a future, approaching a “post-nuclear world”³³. The process of massive reductions in the world's stocks of nuclear weapons has started, and there are no immediate reasons for it not to continue. The present generation of fission reactors is, in numbers and electricity generation capacity, reaching a peak in a few years time and there is no clear sign that there will be a surge of orders for new reactors to succeed it. In the final part of this introduction we will examine these developments further.

1.4 Towards a “Post-nuclear World”? – Implications and Possibilities

At the present time, the nuclear world order, both civil and military, is undergoing the most profound changes since the start of the nuclear era. On the military side, there are for the first time large-scale reductions in the world's nuclear arsenals. Even

³¹. Emphasis in original text.

³². We here have to mention fusion energy. It is possible that a system of fusion energy reactors can be developed with a fuel cycle that could be considered sustainable, i.e., would rely on a very large, although limited, fuel source and would not leave large and long-lived waste problem. Today's efforts are far from such a system, and there is, in fact, no reason at all to believe that a system of this kind that is economically viable, compared to renewable energy sources, could ever be developed. Any fusion energy system will, in addition, be a potential proliferation problem as the reactors can be used as neutron sources for production of military fissile material.

³³. In order to avoid possible confusion it is here stated that a future post-nuclear world is not a world that does not use nuclear technology, but rather a world that does not use large-scale nuclear technologies, civil or military, which produce large amounts of long-lived high-level nuclear waste. Radionuclides that are needed for medical or industrial purposes can already today be produced in particle accelerators. In such production only small amounts of relatively short-lived radioactive waste are created.

though very large numbers of nuclear warheads still remain in the nuclear stockpiles the numbers are decreasing daily and the rate at the moment seems controlled by the rate at which the military nuclear establishment can dismantle the weapons. Even though the cuts in numbers have to a large extent involved older nuclear weapon systems that might anyway have lost their role in the military strategy, we now see the cancelling of new weapon systems and indications that we might soon see a cut-off in the production of new military fissile material. It seems reasonable to assume that we will, in the not too distant future, see also a stop in the design and development of new nuclear warheads with an accompanying comprehensive test ban. The dismantling of the nuclear weapon systems has unfortunately not yet led to decisions of how to deal with the fissile material that is freed in this process. The INF and START treaties that have so far been signed have allowed the signatories to take the nuclear warheads back into the stockpiles and some have even been reused more or less directly in new nuclear weapon systems. Soon, perhaps, we will see a system developing also for taking care of the fissile material³⁴. And, as the rationale for keeping the still large nuclear arsenals is slowly but surely undermined with time, the reductions will continue.

On the civil side, the global civil nuclear electric power generation capacity is reaching a plateau and will start to decrease within the next 10 to 15 years, unless large orders for the next generation of nuclear power reactors start to come soon. In the same time-scale there is a large potential for energy saving that is often more profitable than investment in new power generation capacity. In addition, when the time comes to replace today's existing nuclear power reactors, renewable and sustainable energy sources may be able to compete well economically with new nuclear power plants³⁵.

These trends will in the future influence our way of handling both military and civil nuclear issues. If the trends that have started continue, it is possible that a "post-nuclear" world could evolve in the not too distant future, i.e., a world that uses nuclear technology, but does not do so in large-scale systems that produce large amounts of high-level nuclear waste, a world where nuclear weapons are either outlawed or under international control³⁶.

³⁴. Some of these developments are discussed in Chapter 4.

³⁵. In fact, both the development of a new generation of nuclear power reactors and of sustainable energy alternatives are today hindered by the very low price on fossil fuel.

³⁶. This brings up an issue that is important – how nuclear weapons are viewed differently in different cultures. This thesis is written by a Swede. Sweden had an advanced nuclear weapons development programme during the 1950's and 1960's, part of which is briefly described in Chapter 4. In the 1960's there developed a strong popular resistance to the development of a Swedish nuclear weapon that led to a cancellation of the programme and to Sweden's signing of the Non-proliferation Treaty in 1968. Much of the resistance was based on moral grounds. The acquisition and use of nuclear weapons was considered unethical. It may thus be much easier for the author of this thesis, coming from a culture where this point of view is prevailing, to have visions of a world free of nuclear weapons than for a reader from a country that has or aspires to obtain nuclear weapons and may feel differently about the value of such weapons. With the rapidly changing international situation, it is not too difficult to foresee a future shift in how the international system views the role of nuclear weapons.

If one examines this question a little further, one in fact realizes that the only long-term stable international nuclear order is one where no individual country or group of countries has nuclear weapons. Any such "inequality" in the international system will, we believe, invariably lead to

One of the legacies of a post-nuclear world will be the handling and disposal of the nuclear waste from the nuclear era. The costs for this will be large and funding for it is in many countries uncertain³⁷. The present principle, used in most of the countries in the world, is that these problems will be taken care of by future generations that also have nuclear power and that will therefore have the technology and funding (from the utilities producing nuclear electricity in that time) to handle them. This will not be the case in a post-nuclear world, and they may then have to use public funding to dispose of our nuclear waste.

Our generation has started to try to find solutions to the long-term environmental problems of nuclear waste disposal. We have only just started to examine the global security aspect of the problems of direct disposal of spent nuclear fuel. What are the prospects for preventing nuclear proliferation in a sustainable post-nuclear world?³⁸

The world order in such a world would probably have a comparatively easy task to realize and verify a regime that forbids the production of nuclear explosives. First, there is no “legitimate” spread of dual-use nuclear technology. A country can not claim that it needs “civil” nuclear reactors, enrichment plants or reprocessing plants just as an excuse to gain access to the technology that it wants for production of military fissile material. This makes the task much simpler for a safeguard regime. The production of certain products that today are legitimate to produce, and sometimes to trade, could be much more severely restricted. Second, the technical verification of nuclear activities will be simpler. For example, the monitoring of radiation release from a covert military programme would be easier as the general radiation levels in nature, and the existence of certain “indicator” isotopes, would decrease slowly and thus make the discovery of outlets of radiation from such a programme simpler.

On the other hand one can not contest that “the genie has been let out of the bottle”. The knowledge that nuclear weapons can be constructed and how to go about doing so will not easily be forgotten, although with time it might become less widespread than it is today. In fact, no future world order can exist without such knowledge on an international level, unless there is such a deep cultural disruption that the present scientific culture is destroyed. An international safeguards regime will always need to know what to look for. As one of the first generations using nuclear technology, we have to make sure that we do not unnecessarily make the problem more difficult for later generations. The present thesis discusses the implications of this.

nuclear proliferation, just as one of the main stumbling blocks of the present non-proliferation regime is the inequality of the terms of the Non-proliferation Treaty which makes it legitimate for some countries to have nuclear weapons but not for others.

³⁷. Sweden has a relatively advanced system for the funding of the future disposal of nuclear waste as is described further in Chapter 4.

³⁸. Perhaps the term proliferation is a little misleading here. Proliferation is based on the prior existence of something. In a sustainable post-nuclear world it will instead be a question of preventing the development of the first nuclear explosives to exist in that world. We will still, in this thesis call this proliferation, as the regime for preventing such a development is very similar to that which can be developed to prevent nuclear proliferation in its proper meaning.

We end this introduction by stating that the long-term non-proliferation problem for future generations should not be underestimated by a generation that:

- has used nuclear weapons in a war.
- has experienced the threat of global nuclear annihilation for a period of over 30 years.
- has seen a previously considered stable global nuclear superpower fall apart with great concern over what happens with its nuclear weapons and over the spread of nuclear material and know-how from its military nuclear complex.
- has seen a number of countries develop a covert nuclear weapons potential
- would have been concerned if one specific country in the world system at the beginning of the 1990's were to have had access to an advanced civil nuclear power programme, or acutely concerned if the same country would have had access to a nuclear spent fuel repository established by a generation using nuclear power 1 000 years ago.

Let us now start the main discussion.

PART I

REVIEW OF MILITARY AND CIVIL NUCLEAR TECHNOLOGY

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2. THE PRODUCTION OF MILITARILY USABLE FISSILE MATERIAL

In this chapter we will review the technologies for the production of fissile material¹ that can be used for the construction of nuclear explosives. We will try to compare the availability and technological complexity of different methods in order to be able to predict which method would be the preferable choice for a future society that decides to gain access to a nuclear explosive.

It is important to understand that the method chosen is dependent on many factors, many which are not always predictable. Let us take an example. During the Kuwait crisis and war 1990-1991 there was much speculation on whether Iraq had access to fissile material that it could use to produce a nuclear explosive. Many indications had been given that the Iraqis were working on a centrifuge isotope separation plant that could produce uranium of a quality suitable for nuclear weapons production². Such technology is being used in the civil nuclear sector in some countries to produce fuel for nuclear power plants. It was possible that Iraq would try to gain access to this technology for the production of military fissile material. In addition, Pakistan had in principle already shown that this was a possible route to take³. After the war, equipment was found that showed that the Iraqis had indeed followed this path. But, more importantly, other equipment was found that showed that the Iraqis had also tried to use another isotope separation technology, namely electromagnetic separation and had done so with some success⁴. Many persons, even experts on nuclear non-proliferation, showed surprise.

But, should they have been so surprised? Electromagnetic separation of uranium was the method used by the United States during the Second World War to produce the first weapons-grade uranium that had ever been made. It must have been one obvious choice also for the Iraqis. However, electromagnetic separation has never been used to produce fuel for civil nuclear power plants. The energy needed to do this is too large to make it economic. In addition, the technology had also since long been abandoned on the military side. It would seem as though the thinking of the world outside Iraq, before and during the war, only relied on the very narrow perspective that just because the technology was not used by the rest of the world it would not be used by Iraq⁵.

There is an important lesson to be learnt here, a lesson that is of high relevance

¹. A short comment on the term "fissile material" may be appropriate. Many heavy nuclides are capable of being fissioned, i.e., they are fissionable. Only a few are fissionable at low neutron energies, i.e., by thermal neutrons, a process that allows the creation of a chain reaction. Nuclides that are fissionable at all neutron energies are said to be fissile. Some materials that are fissionable only by fast neutrons may contribute to the yield of a nuclear explosive due to the large number of fast neutrons that may be produced during the explosion.

². See, for example, Albright & Hibbs (1991A) and Mark (1991).

³. See, for example, Albright (1987A), Albright (1987B) and Albright (1989).

⁴. See, for example, Albright & Hibbs (1991B), Albright & Hibbs (1991C), Maddox (1991) and Norman (1991).

⁵. Incidentally, this was also the case for the author of this thesis. He has learnt his lesson.

for the discussion in this thesis. It is very difficult to foresee which technology, or for that matter which type of fissile material, will be used by a country striving for a nuclear explosive. The availability of technology, the nature of the threat and the time available, all play an important role.

In the following pages, we will first give an overview of the production of militarily usable fissile material, both in the military and the civil nuclear sectors⁶. While doing this we will compare the two sectors and show similarities and differences that are of importance⁷. We will then study, in a little more detail, the different processes that are possible to use to produce militarily usable fissile material.

In the final part of this chapter we will also define different types of fissile material, in terms of their isotopic content, such as the concepts are used in this thesis. In this connection, we will, for a few important isotopes, list some characteristics that are important for the further discussion in this thesis.

2.1 An Overview of the Production of Militarily Usable Fissile Material⁸

Figure 2.1 is a schematic diagram that shows the main flows in the military and civil systems for the production of fissile material⁹. All efforts to produce nuclear explosives or nuclear energy rely on a source of natural uranium, mined as a mineral,

⁶. There is no such material readily available in nature. A relatively large-scale industrial process has to be used to get access to fissile material.

⁷. This subject is quite controversial. Hannes Alfvén, the Swedish Nobel Prize winning physicist, has stated that “nuclear power and nuclear weapons are Siamese twins” (see, for example, Alfvén 1975, p. 68). On the other hand, many scientists working within the civil nuclear establishment will deny that there is any connection of importance between the two.

On one hand, the civil nuclear technology is a “spin-off” from the military technology, using the same basic techniques. On the other hand, the civil nuclear establishment has tried hard to make the distinction as clear as possible. The civil nuclear power sector has, at least in some countries, tried to make its nuclear fuel cycle as proliferation resistant as possible. One can, for example, choose a type of nuclear power reactor that is difficult to operate in a mode that produces high quality plutonium for weapons and one can refrain from reprocessing and recycling plutonium. The distance between the civil and military nuclear sectors is different in different countries. In the United States the civil nuclear sector tries to separate itself as far as possible from the military nuclear sector. In France, however, the connection between the two is much more apparent.

⁸. In this thesis we will not discuss any of the many “alternative” nuclear fuel cycles that could be used instead of the presently used cycles and future plutonium recycling in fast breeder reactors (FBRs). The thorium/²³³U breeder fuel cycle is perhaps the one that has been seen as the most promising and it has been developed quite far in India (Basu & Srinivasan 1990). This fuel cycle is also described in, for example, Dukert (1970), Wallin (1972), Feiveson & Taylor (1976), Feiveson (1978), Feiveson, von Hippel & Williams (1979), Lovins (1979A), von Hippel & Feiveson (1979), Lovins (1979B), Galperin (1986). There are also a few types of new breeder reactor constructions for alternative plutonium breeding fuel cycles. Some have been, or are being built, as prototypes, but most are still on the drawing board. In addition, there are numerous suggestions for diverse constructions of hybrid systems that combine fission with fusion, or that involve the use of particle accelerators.

⁹. In the civil sector these are often called nuclear fuel cycles.

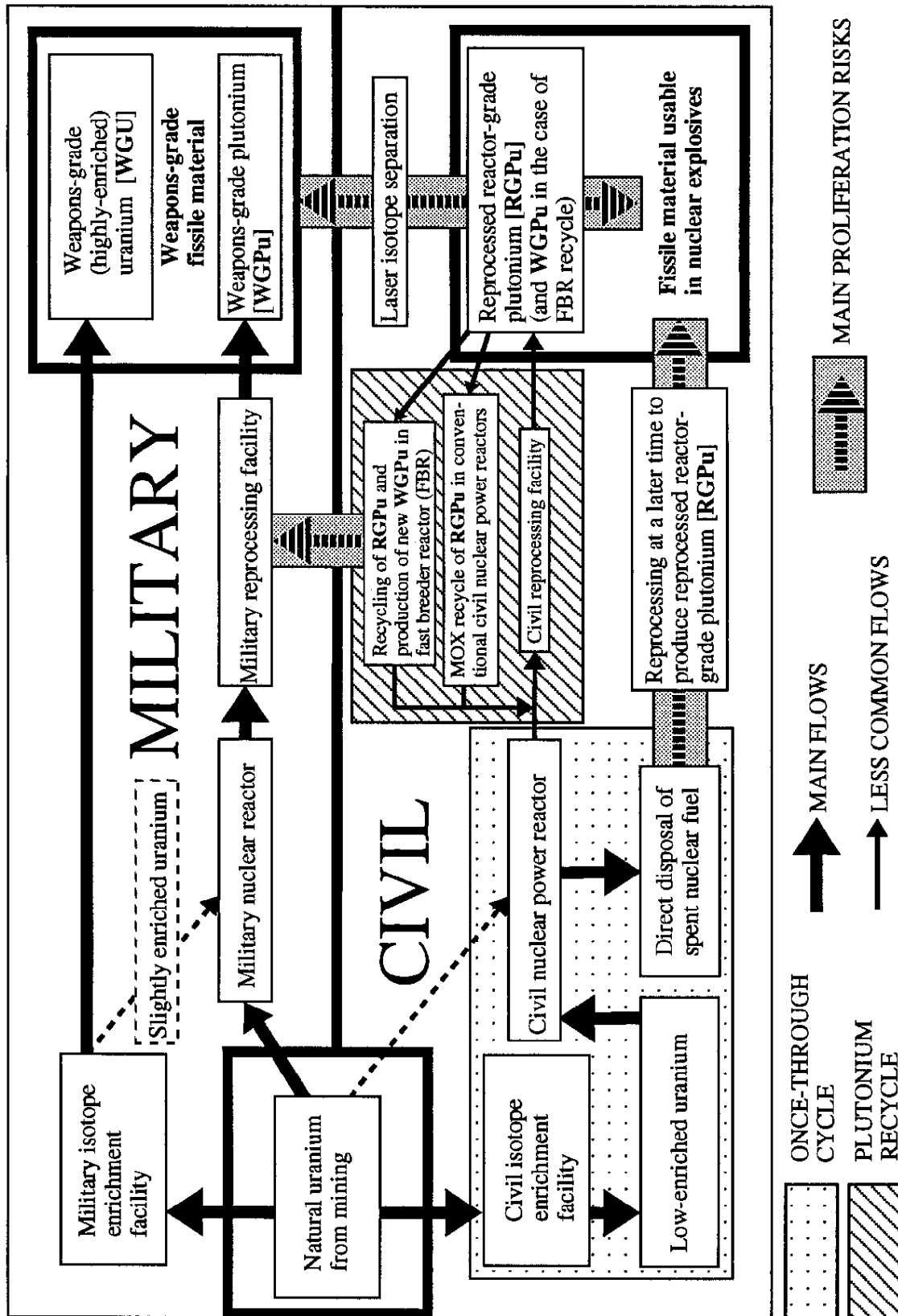


Figure 2.1. Schematic diagram of flows of fissile material in the civil and military nuclear establishment

as the basic raw material¹⁰. This is represented by the thick box in the left part of the picture. After the uranium ore has been removed from the ground it is processed so that the uranium is in a form suitable for further use. A number of arrows lead from the natural uranium box. The upward arrows lead into the military sector and those that flow downwards lead into the civil sector¹¹. The thick solid arrows in the figure show the most common paths, both on the military and the civil side, that have been or are currently used. On the civil side the thick arrow leads into an isotope enrichment plant where the natural uranium is enriched for use as fuel in civil nuclear power reactors. The isotope separation, in which the relative content of the fissile isotope, uranium-235 (^{235}U), is most commonly raised to approximately 3%, takes place in an isotope enrichment plant. Different methods for isotope separation of uranium are described later in this chapter. On the military side, the same type of plant¹² is used to raise the relative isotopic content of ^{235}U to over 90%, thereby producing highly-enriched uranium¹³. The resulting fissile material, which is of weapons-grade quality, i.e., weapons-grade uranium (WGU) is represented in the thick upper box to the right in the figure.

In the same box we also find the second common type of fissile material used in the military nuclear arsenals today, namely weapons-grade plutonium (WGPu). As is shown, this plutonium is produced in special military nuclear production reactors¹⁴. These are most often fed with fuel containing natural uranium, i.e., un-enriched uranium. Because these reactors use natural uranium as fuel they have to use other materials than ordinary light water for moderation and cooling. Most common materials are heavy water or graphite and a gas^{15,16}. After the fuel has been irradiated in the reactor it is taken to a reprocessing plant where the WGPu is removed and then used for the construction of nuclear explosives.

On the civil side, as mentioned above, similar types of nuclear reactors, nuclear power reactors, are used to generate electricity. The most common reactor types are variations of light-water reactors using low-enriched uranium as a fuel^{17,18}. On the civil side, the flow goes through the isotope enrichment plant, then through the nuclear power reactor and into a box for direct disposal of spent fuel as nuclear

¹⁰. Natural uranium has an isotopic composition of approximately 0.7% of the uranium isotope uranium-235 (^{235}U), the rest being uranium-238 (^{238}U).

¹¹. There are few arrows that show a flow from the military to the civil side in the diagram, as will be discussed further on. These are, however, not the only connections between the military and civil nuclear sectors. Most of the boxes on the top half have their equivalents on the bottom half and vice versa. The same technology is used, albeit not always in systems of identical construction.

¹². These plants are actually in most cases the same. There are, however, isotope enrichment plants that have been built exclusively for civil enrichment.

¹³. In this thesis, weapons-grade uranium is defined as containing 93.5% ^{235}U and 6.5% ^{238}U .

¹⁴. Some of these reactors are, however, also used to produce electricity.

¹⁵. "Heavy" water is water where the hydrogen atoms have been replaced with deuterium (^2H). Heavy water is present in ordinary water in very low concentrations but can be separated out.

¹⁶. Slightly enriched uranium containing between 0.7 and 1.8% ^{235}U has, however, sometimes been used as a fuel in military nuclear reactors, as indicated by the dotted line.

¹⁷. "Light" water is ordinary water. It is used both as moderator and coolant.

¹⁸. Some civil nuclear power reactors use natural uranium as fuel which is indicated by the dotted line. In addition, some nuclear power reactors use slightly enriched uranium ($^{235}\text{U} \approx 1.0\text{-}1.8\%$) as fuel. This is not even indicated in this simplified diagram.

waste. This is called the “once-through nuclear fuel cycle“ and it is surrounded by a shaded box. The once-through nuclear fuel cycle is the most common presently used fuel cycle. In the nuclear power reactors, plutonium of reactor-grade quality, i.e., reactor-grade plutonium (RGPu), is produced. The difference between RGPu and WGPu is described in a later section in this chapter.

A smaller flow goes from the box indicating civil nuclear power plants into a box that is normally referred to as plutonium recycling. This box therefore represents a long-term plutonium economy. The spent nuclear fuel is reprocessed in a reprocessing plant that uses the same technology as the military reprocessing plants. The reprocessed RGPu can either be used as so called mixed-oxide (MOX) fuel in conventional civil nuclear power reactors or it can be used as fuel in the cores of fast breeder reactors (FBRs). MOX fuel contains a mixture of uranium oxides and plutonium oxides in a combination so that the fuel will be as similar as possible to low-enriched uranium fuel as regards reactor physical characteristics. FBRs burn the plutonium in the core of the reactor. At the same time fresh plutonium is bred from the large fraction of ^{238}U in a natural or depleted uranium blanket that surrounds the core. This plutonium can then be used as fuel in the core and therefore the FBR in principle is run on ^{238}U that is much more abundant than ^{235}U . This was for a long time seen as the inevitable long-term future for nuclear power, as the ^{235}U in natural uranium that could be economically mined would not last for much longer than the fossil fuel resources¹⁹.

The recycling of RGPu has not met with any commercial success so far, neither as MOX fuel, nor as FBR fuel. The risks for proliferation made many countries, among them the United States and Sweden, forgo the technology in the late 1970s and the early 1980s. The economic disadvantages of those technologies have made other countries hesitant since. MOX fuel recycling is still carried out to some extent, but is presently only “economical“ compared to low-enriched uranium fuel when the plutonium is considered “free“ because of sunken costs in reprocessing plants (OECD/NEA 1989).

There are indeed risks concerning nuclear proliferation when a plutonium economy is developed. Large amounts of plutonium are transported and used as fuel in reactors. After reprocessing, much of the work needed to use the plutonium in a nuclear explosive has already been done. Reprocessing is a relatively complicated chemical process, especially if high purity of the plutonium is to be achieved. In addition, the spent nuclear fuel is highly radioactive and is therefore very difficult to handle. Reprocessed plutonium, however, in metal form or as an oxide is much easier to use as raw material for a nuclear explosive.

The risk for such use is indicated by the thick striped downward arrow from the box containing reprocessed RGPu representing the possible use of this material for the construction of nuclear explosives. The limits and possibilities of using RGPu in

¹⁹. The same amount of natural uranium can be used to generate approximately 50-100 times as much nuclear electricity if plutonium is recycled in FBRs as if the uranium is used in a once-through fuel cycle.

For an evaluation of available global uranium resources, see OECD/NEA/IAEA (1989A).

nuclear explosives are evaluated in the next chapter.

Another thick striped arrow leads into the thick-walled box. This arrow points to the main subject of this thesis, the possibility of using fissile material disposed of as waste for a nuclear explosive at a later time, perhaps very far into the future. We will not discuss this further here but will instead refer the reader to the second part of the thesis where this subject is examined in detail.

There are two more flows indicated similarly. They lead from the civil to the military side of the figure. The arrow leading from the fast breeder reactor indicates that the plutonium that is bred in the mantle of the reactor is of weapons-grade quality. Such plutonium, when reprocessed for recycling, could just as well go to a military programme. The second arrow is labelled laser isotope separation and leads directly from RGPu to WGPu. This process is also very important for the discussion in this thesis. Traditionally isotope separation techniques have used mass or volume differences of heavy isotopes in order to be able to separate them. As we shall see in the next section, this is possible for uranium where the isotopes ^{238}U and ^{235}U are sufficiently different in mass. This is not the case for the plutonium isotopes that one would want to remove in order to make RGPu into WGPu. The process would be too inefficient and it is easier to build a reactor to produce WGPu directly. During the last decades however laser isotope separation techniques have been developed both for uranium and plutonium²⁰. This means that today technology is available, at least in technologically developed countries, that allows the conversion between RGPu and WGPu. This is discussed further in a special section at the end of this chapter.

2.2 Production of Weapons-grade Uranium²¹

Weapons-grade uranium (WGU) is produced by isotope separation of natural uranium²². WGU has an isotopic content of 93.5% ^{235}U and 6.5% ^{238}U compared to the 0.7% ^{235}U and 99.3% ^{238}U in natural uranium. Such separation is much more difficult than chemical separation of different elements. In the case of uranium, most isotope separation methods rely on the small mass difference between the isotopes

²⁰. In small amounts, electromagnetic isotope separation is also possible for all elements, including plutonium. See, for example, Love (1973).

²¹. This section is quite brief in its discussion. For more information the reader is referred to Beckman (1969), Love (1973), Wallin (1973), Jensen et al. (1976), Casper (1977), Krass (1977), Zare (1977), Olander (1978), Letokhov (1979), Villani (1979), Jensen, Sullivan & Finch (1980), Becker & Kompa (1982), Davis, Holtz & Spaeth (1982), Krass, Boskma & Smit (1983), Stern & Paisner (1985), Cochran et al. (1987A), Cochran et al. (1987B), Cochran et al. (1989), Kokoski (1990) and Albright & Hibbs (1991B).

²². WGU is also used for two other purposes than in the construction of nuclear explosives: as fuel in naval propulsion reactors on board some submarines and military ships, and in civil research reactors. It is then most often called highly-enriched uranium (HEU). The latter use is now more or less discontinued, due to proliferation risks, and most research reactors have been reconstructed to accept fuel enriched to 20% of ^{235}U .

WGU is also called Orallloy. The name comes from Oak Ridge alloy, and was the code-name for WGU during the Manhattan Project. Oak Ridge was the site for the first electromagnetic separators and later for a gas diffusion plant, which has now been mothballed.

^{235}U and ^{238}U . This difference is comparatively small compared to the mass differences between isotopes of lighter elements. In addition, the separative work that has to be carried out is large as the relative amount of ^{235}U has to be increased from such a small percentage, under 1%, to a value over 90%.

In most of the isotope enrichment methods described below, the separation is carried out in many stages, and in each stage only a small increase in isotope enrichment is achieved. These stages are then connected in large cascades. Because the enrichment is so small in each stage the cascades have to contain a large number of stages. This makes WGU production plants relying on these methods very large, occupying major areas of land. This is important, because it is much easier to detect the covert construction of such a plant, for example by satellite surveillance followed by on-site inspection, than if the method could produce WGU from natural uranium in only a few steps. Many machines might be needed for the production of larger amounts of WGU in the latter case, but they could be distributed on many sites. We will return to this subject briefly at the end of this section.

The development of methods for isotope separation of uranium has historically gone through two basic stages. The first was from the mid-1940s to the 1960s when military production of WGU was of primary importance²³. During the second period, from the 1960s and onwards, the commercial interest in isotope separation of uranium for the production of low-enriched uranium for nuclear power plants motivated the development of new, more efficient, methods for isotope separation. The first developed methods required very large energy inputs and, after all, one did not want to put in more energy into the process than one could derive from the enriched uranium²⁴. With the rapid expansion of nuclear power during the 1970s, many new isotope enrichment plants using new technologies were built and the old military plants were improved so that their efficiency was increased and they could compete on the civil market. Soon there was an overcapacity on the market, a situation that still remains today²⁵.

The first method for isotope separation that was used historically was the separation by electromagnetic means. This method was used by the United States during the Second World War and for a short period after. The method has presently become of interest again since, as mentioned above, this technology has also been used by Iraq. The device that is used is called a calutron²⁶ and a schematic drawing

²³. The United States stopped its production of WGU for nuclear explosives in 1964. The production capacity had originally been very large and when the use of WGPu became more important than that of WGU in explosives, there was soon a large overcapacity for WGU enrichment. In military circles it is often more difficult to stop a project than to start it and large stocks of WGU reserved for explosive purposes were built up before production was stopped. There was still a need, however, for the production of highly-enriched uranium for naval propulsion and research reactors.

²⁴. As long as the processes were being utilized solely for military purposes, there was no great incentive to increase energy efficiency.

²⁵. There is actually a similarity here to the economy of MOX recycling using "free" plutonium discussed above. The market for civil uranium enrichment is such that investment costs in the isotope enrichment plants have had to be considered as "sunk costs" and thus the nuclear industry does not pay the full costs for the nuclear fuel.

²⁶. The name is short for California University Cyclotron. This was the first calutron ever constructed, in 1940, and it was based on a cyclotron. The United States built its first calutron isotope enrichment

of such a machine is shown in figure 2.2.

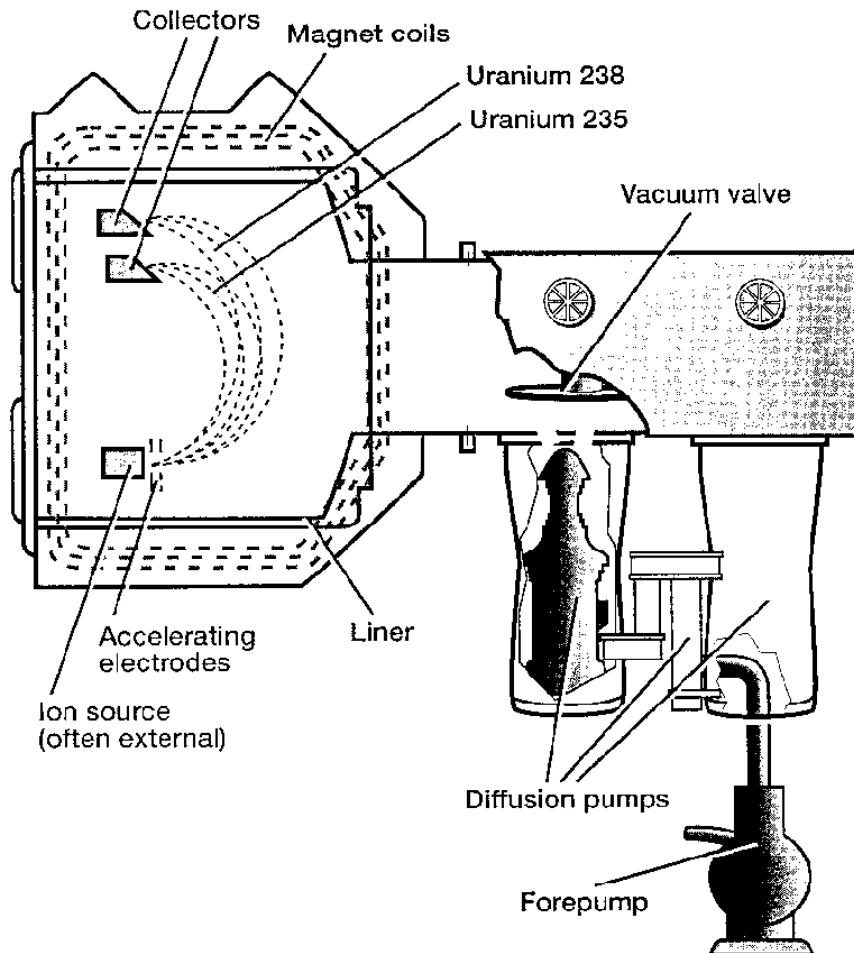


Figure 2.2. A schematic drawing of a calutron (from Albright & Hibbs (1991B, p. 19))

The principle is quite simple. The isotopes to be separated are ionized and then accelerated through a strong magnetic field created by a very large electromagnet. The accelerating particles are deflected in the magnetic field and since the deflection is mass dependent, the lighter particles are bent off more. When the isotopes hit a collector they are therefore separated by mass. The process is very inefficient and requires very large amounts of energy²⁷. Already by mid-1945, a new isotope

plant in Oak Ridge. At its peak in 1945 there were over 1 100 separating units working. There was a shortage of copper for windings during the war. At Oak Ridge, where some sort of security could be kept, 15 000 tonnes of silver from the Federal Reserve were used for this purpose.

²⁷. For this reason the method is totally unsuitable for the production of low-enriched uranium for nuclear power plants. Therefore the International Atomic Energy Agency (IAEA) could announce that Iraq had breached its obligations under the Non-proliferation Treaty (NPT) as it had used a nuclear technology that was purely military. In the case of the development of centrifuge separation

enrichment process, gaseous diffusion, had been proven feasible and most of the calutrons at Oak Ridge were dismantled²⁸.

For a heavy element, mass difference between ²³⁵U and ²³⁸U is relatively large. In a calutron this is not so important and other elements, such as plutonium, can be separated with this technology. The technologies that were developed after the war, gaseous diffusion, gas centrifuge techniques and gas nozzle techniques are not applicable to the separation of plutonium isotopes. In the last method in this section, when we discuss laser isotope separation, we will again consider the isotopic separation of plutonium.

Gaseous diffusion became the main isotope separation technique after the war and very large complexes were constructed in all the countries that were aiming for a nuclear weapons potential, i.e., the United States, Britain, France, the former Soviet Union and China. The gaseous diffusion isotope separation technique relies on the fact that the diffusion rate of a particle is mass dependent so that lighter particles move slightly faster, on the average. The uranium is first converted into uranium hexafluoride (UF₆) which is a gas at temperatures above 56.5°C. This gas is then forced past a system of diffusion barriers and on the opposite sides of the barriers there is a flow of material where the isotopic content of ²³⁵U is slightly higher. Figure 2.3 shows three stages containing diffusion barriers. The barrier tubes are almost 3 m long. The stages are connected in a long and complicated chain of cascades so that on one side there is an output of small amounts of uranium of high enrichment and on the other side large amounts of uranium which is depleted²⁹. There can be thousands of stages connected in cascades in one gaseous diffusion plant. An example of such a plant is shown in figure 2.4.

techniques this is not possible. The technology has dual use, and Iraq could always, as other countries have done, claim that the development of this technology is for civil purposes. That such a claim is not, as it perhaps was during the 1960's and 1970's, a plausible explanation today is another matter.

²⁸. Some were kept and used for small-scale isotope separation of various elements. See, for example, Love (1973).

²⁹. The number of stages x in an enrichment facility that are in principle needed in order to enrich an amount of uranium from $A\%$ to $B\%$ if each cascade delivers a product that is $y\%$ richer in ²³⁵U can be calculated as follows:

$$A \left(1 + \frac{y}{100} \right)^x = B \quad \Rightarrow \quad x = \frac{\ln \left(\frac{B}{A} \right)}{\ln \left(1 + \frac{y}{100} \right)}$$

The separation gain y varies with the separation method used but is on the order of 0.5% for gaseous diffusion. This means that in order to raise the ²³⁵U isotope concentration from 0,7% to 3% 292 stages are needed. Another 690 stages are needed to reach 93.5% ²³⁵U, i.e., WGU. This means a total of 981 stages to go from natural uranium to WGU.

In reality, the number of stages in an isotope separation plant is much higher, because if the material was only fed once through there would be enormous losses of material enriched in ²³⁵U in each step. Therefore the cascades are connected so that there is a resulting "tail" product of depleted uranium. This uranium often has a ²³⁵U content of 0.2%. An ideal cascade with a tail feed of 0.2% would for a gaseous diffusion plant with the above separation gain require 1 100 stages to produce 3% enriched uranium from natural uranium and over 3 300 stages to produce WGU from natural uranium feed (Krass et al. 1983, p. 113)

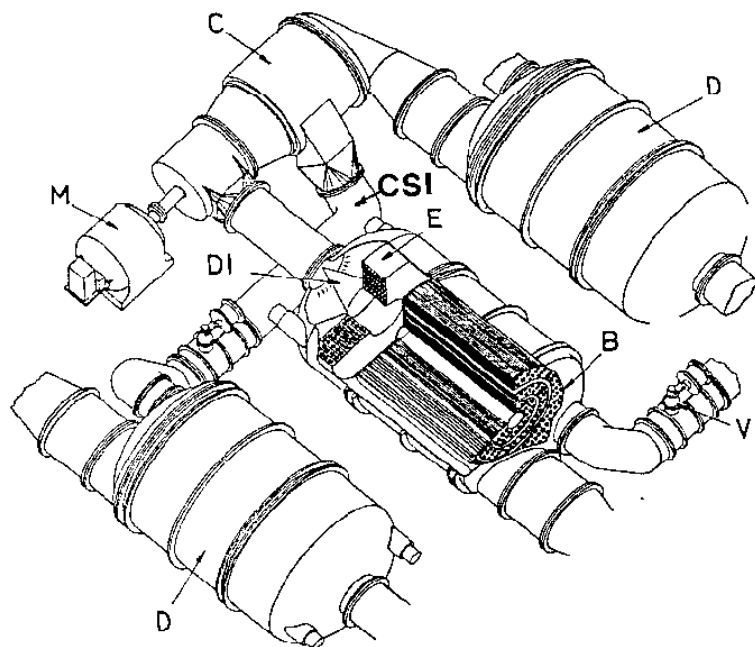


Figure 2.3. Stages of a gaseous diffusion isotope enrichment plant (from Villani (1979, p. 132))

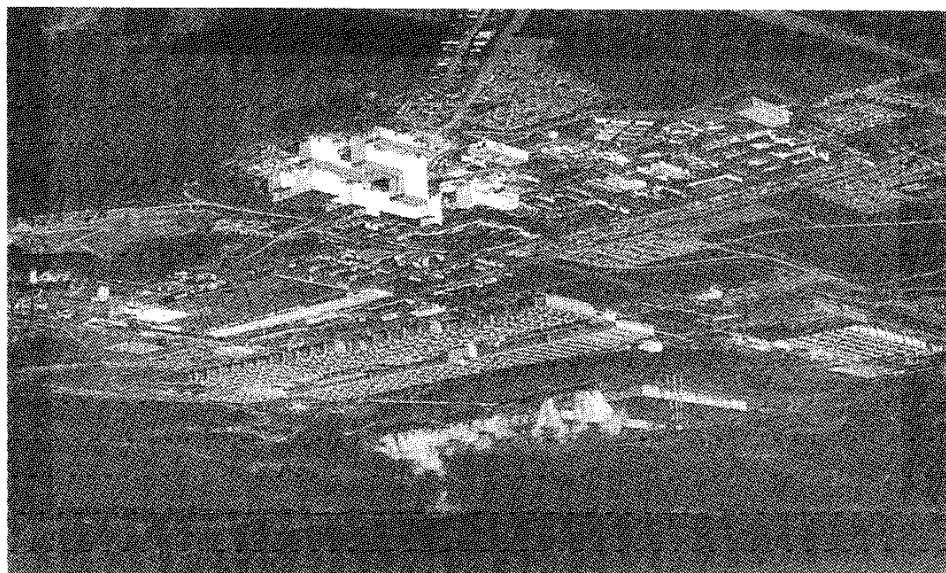


Figure 2.4. Aerial photograph of the Oak Ridge gaseous diffusion plant (from Cochran et al. (1987B, p.126))³⁰

³⁰. This plant is placed on standby since 1985 (Norman 1985, Cochran et al. 1987B, p. 128).

When the need for low-enriched fuel for nuclear power reactors began to grow in the late 1970s, new technologies were mature that were more efficient than gaseous diffusion. The two main types of systems that were developed and commercially used were centrifuge separation and gas nozzle separation. Both process the uranium in the gaseous UF_6 form. In both methods large cascades of units are connected in a similar manner to that used in the gaseous diffusion technique³¹. In the centrifuge method each stage is constructed as shown in figure 2.5.

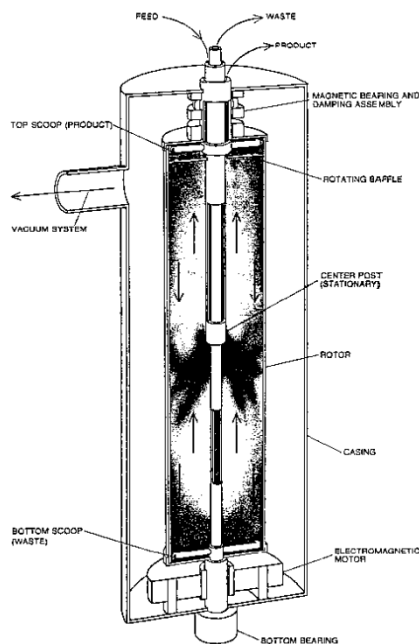


Figure 2.5. Interior of a centrifuge stage (from Olander (1978, p. 29))

The difference in density between the $^{235}UF_6$ and the $^{238}UF_6$ gases as they rotate in the centrifuge separates them enough so that a product that is slightly enriched can be fed into the next stage, while a waste stream flows out another way³². The stages are then, once again, connected in cascades.

A stage from the cascade in the nozzle method is shown in figure 2.6. The

³¹. Because the separation gain γ is higher for these methods, in the case of gas centrifuges much higher, than for gaseous diffusion, the number of stages needed in each cascade is lower than the value discussed in note 29. For gas centrifuges the value of the separation gain γ is 40%, or perhaps higher, and for gas nozzles 1.5%. This means that 15 cascades are needed for gas centrifuges and 329 cascades are needed for gas nozzles to increase the ^{235}U content in uranium from 0.7% to 93.5%.

In accordance with the discussion at the end of the same note, in reality over 40 stages are required for gas centrifuges and about 1700 stages for the gas nozzle method to produce WGU using natural uranium and leaving 0.2% tails.

³². The density difference is a consequence of the difference in mass.

uranium gas is forced to expand through a nozzle with a semicircular wall that has a very small radius of curvature. If the speed of the gas is very high the centrifugal acceleration on the gas particles can be considerable. The difference in density is once again the important factor and the heavier $^{238}\text{UF}_6$ gas is to a larger extent forced closer to the wall. A knife edge skimmer splits the gas flow into two parts, one with a higher concentration of ^{235}U than the other.

Both the gas centrifuge and the gas nozzle isotope separation technologies have been commercialized for the production of low-enriched uranium for fuel in nuclear power reactors.

The last method for uranium isotope separation that we will discuss is laser isotope separation (LIS). This method has not been put into military or commercial use so far, but it is clearly the technology that will be used if ever a new uranium isotope enrichment plant will be needed. When the United States investigated what type of replacement facility should be built for the ageing gas diffusion facilities, both gas centrifuge and LIS technologies were developed. In 1985 it was decided that the United States should build a LIS facility when a replacement was needed³³. Such a decision has, however, not yet been taken. This can be said to be mainly due of the overcapacity of the global uranium enrichment facilities³⁴.

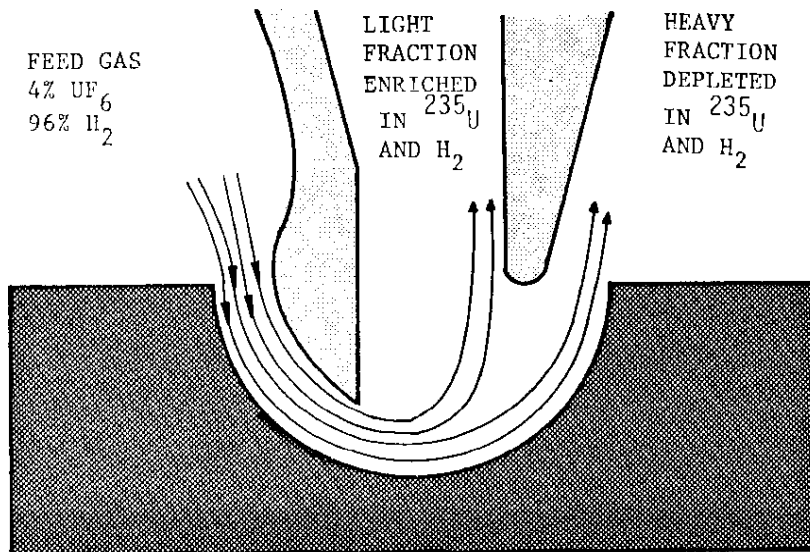


Figure 2.6. A gas nozzle for isotope separation (from Krass (1983, p. 137))

33. In fact, close to USD 3 billion had already been invested in the construction of a centrifuge enrichment facility before this decision was taken (Norman 1985).

34. The technology was also found usable in the development of LIS techniques for plutonium as discussed in a section below, even though the plans for building such a facility in fact also have been shelved.

LIS technology uses the fact that the excitation and ionization energies of the atoms or the dissociation energy of molecules containing the isotopes differ slightly. This means that if one can tune a light source so that it can very exactly shine in one wavelength, it is possible to affect just the ^{235}U atoms, while leaving the ^{238}U atoms unchanged³⁵.

Lasers have this quality as a light source. They emit light at a very exact wavelength. In addition there now exist lasers that are “tuneable“, i.e., that can be made to emit light at the specific wavelength that is needed for the isotope that is to be ionized. There are two main variants of LIS, atomic vapour LIS and molecular LIS. The methods are similar, but the former utilizes the ionization of atoms while the second utilizes the dissociation of molecules.

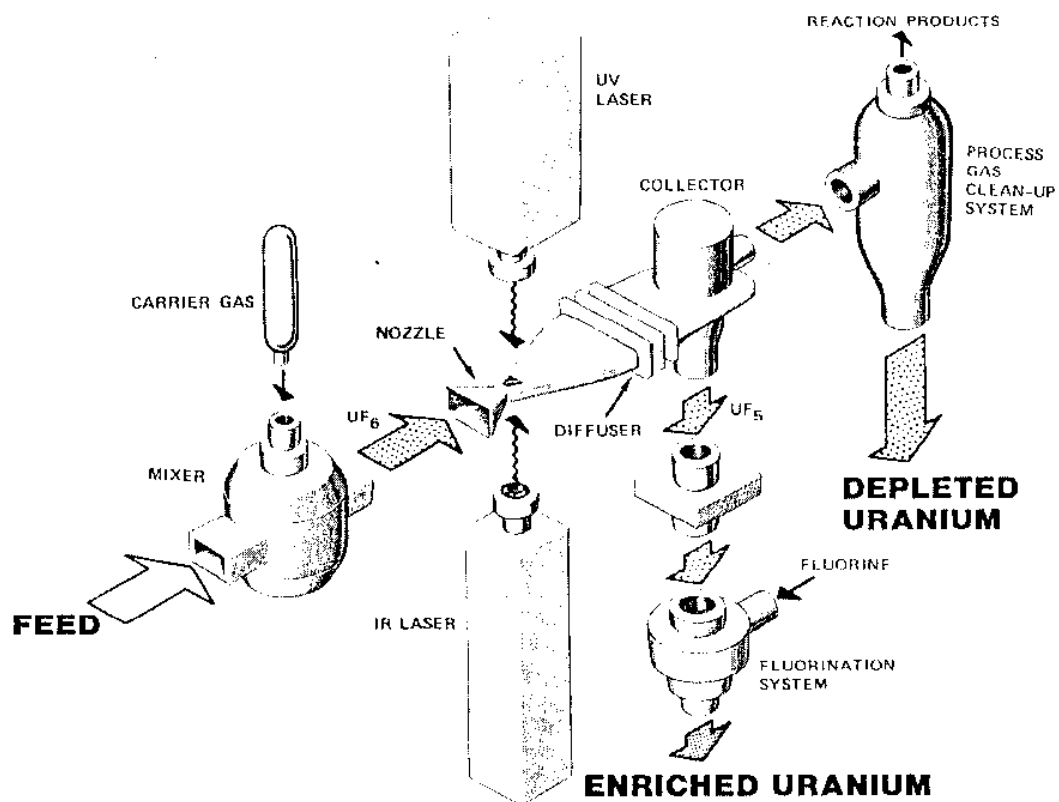


Figure 2.7. Schematic drawing of a molecular laser isotope separation facility (from Krass (1983, p. 168))

A schematic diagram depicting a molecular LIS facility is shown in figure 2.7. In the diagram we see the input of molecules of uranium hexafluoride (UF_6) gas from the left. These are mixed with a carrier gas and then fed through an expansion nozzle so that the UF_6 gas is cooled³⁶. The gas then passes through the laser light

³⁵. This is a simplification. Normally lasers tuned to several wavelengths are used simultaneously.

³⁶. This is necessary in order to put as many as possible of the uranium atoms in the ground state. In the UF_6 gas at normal temperatures, i.e., above 56.5°C , the collisions between the molecules give the

beam³⁷. In the laser beam the $^{235}\text{UF}_6$ molecules are dissociated, losing one fluorine atom and the resulting $^{235}\text{UF}_5$ molecule, which is a solid, falls as “laser snow“. It is filtered and fluorinated to become UF_6 again, and it can then be passed through the process again to further increase the enrichment.

Figure 2.8 shows a schematic diagram of the atomic vapour LIS process. It is very similar to molecular LIS, but instead of using UF_6 , the uranium atoms are vaporized by an electron beam and drift upwards towards the horizontal tails collector on top. When they pass through the laser beam, the ^{235}U atoms are ionized, and they are then collected on the vertical product collectors by a combination of electric and magnetic fields³⁸. The ^{238}U nuclei are not ionized and are collected on the tails collector.

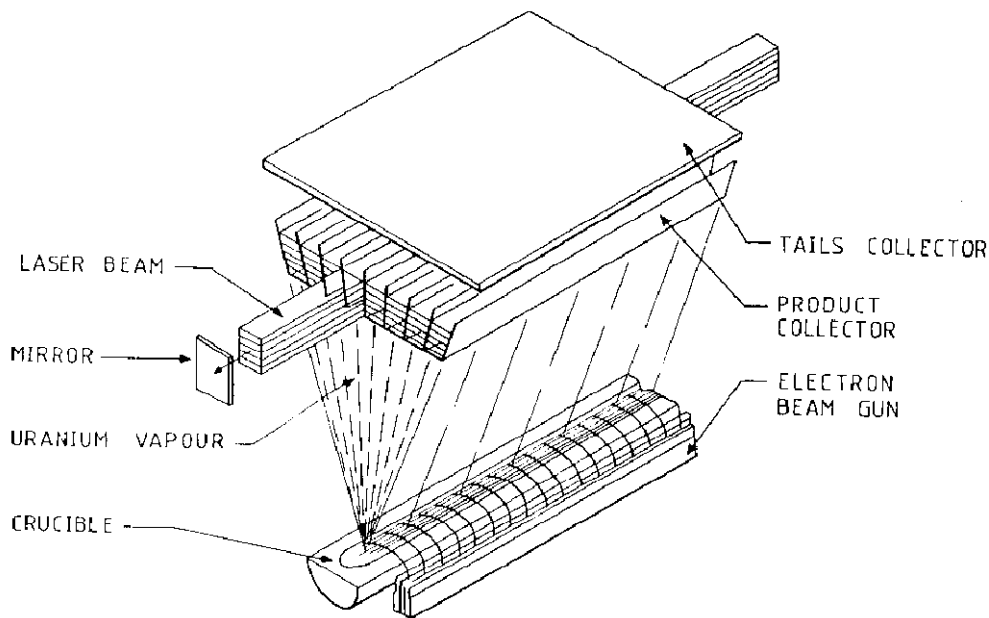


Figure 2.8. Schematic diagram of the atomic vapour LIS process (from Krass (1983, p. 161))

The separation gain for atomic vapour and molecular LIS is approximately 10 to 15 times³⁹. Using the higher figure this means that in one pass would make low-enriched uranium (3% ^{235}U) from depleted (!) uranium (0.2% ^{235}U) of which there

atoms a large variation of vibrational energy, making it difficult to use just one laser wavelength for excitation.

³⁷. In this case a tuneable laser is not needed for uranium. A 16 μm infrared laser can be constructed that puts the molecules in their lowest vibrational state, then the $^{238}\text{UF}_6$ molecules can either be raised in vibrational energy until dissociation by a number of photons from a CO_2 -laser emitting infrared light at 10 μm or raised to dissociation energy directly by an ultraviolet laser (Krass et al. 1983).

³⁸. The laser system that is used in the atomic vapour LIS utilizes three or four tuneable dye lasers (Krass et al. 1983, pp. 162-163).

³⁹. Compare with note 29.

are large amounts available as “tails“ from earlier uranium enrichment. A second pass would make the uranium close to WGU⁴⁰.

In the United States, when LIS technology was developed, the two big nuclear weapons laboratories put their efforts into one of these technologies each. Los Alamos chose to develop molecular LIS and Lawrence Livermore chose to develop atomic vapour LIS. Each developed the method for both uranium and plutonium. The technology that the United States has chosen has been the atomic vapour LIS, both in the case of uranium and plutonium. It is, however, not clear that this decision necessarily means that molecular LIS is a less feasible technology and the decision was taken among some controversy (Norman 1982).

Finally, let us now, once again, return to the subject of the possibilities for covert construction of a uranium isotope enrichment plant. The two methods that do not rely on cascade technology are electromagnetic separation and laser isotope separation. If we return to the case of Iraq, we here have one explanation why most experts were so surprised that the Iraqis were using this technology. It was not easy to discover. No big industrial site was needed⁴¹. In addition, the equipment could be constructed to a large extent by indigenous means and materials. Laser isotope separation here shows similarities, except for the question of technology and equipment. Even though most of the equipment that is needed for the construction of such a plant is of dual use, it would today have to be imported by most countries that might have covert aspirations to construct nuclear explosives and the export control regimes could discover such attempts. In addition there seems to be quite a strict black-out to prevent the spread of information about laser isotope separation technology today⁴². Neither of these factors can be expected to prevail for very long. In a not too distant future both the technology and the know-how will be global. The situation regarding the spread of technology and know-how for laser isotope separation is today similar to that of electromagnetic separation in the late 1940s. One can possibly expect that if the situation that occurred in Iraq were to be repeated in fifty years time, laser isotope separation would figure very strongly in the course of events.

2.3 Production of Plutonium Usable in Nuclear Explosives

Plutonium is produced in a nuclear reactor. The core of a nuclear reactor with fresh fuel contains only ²³⁵U and ²³⁸U, though the relative ratio between the two may vary depending on the type of reactor. The most important process for the production

⁴⁰. There is thus hardly any need to discuss cascading in this case.

⁴¹. This situation is very different from the case, for example, of the Pakistani Kahuta centrifuge separation facility for covert production of WGU. This site is clearly visible even on civil remote sensing satellite imagery and would clearly be a site for inspection under a strengthened future nuclear non-proliferation regime. In principle though, a covert programme using gas centrifuges would be easier to distribute than one using gas diffusion or gas nozzle technology as the number of cascades needed is not exceptionally high (see note 29 and 31).

⁴². Searching in scientific data bases on the keywords laser isotope separation gives relatively little information for a technology, with civil applications, that has been and still to a certain extent is under rapid development.

of plutonium is the capture of a neutron by the nucleus of ^{238}U turning it into ^{239}U ⁴³. This uranium isotope within days decays via ^{239}Np into ^{239}Pu . In figure 2.9 this process is marked by thicker arrows. The chain of such arrows continues to the left from ^{239}Pu showing that the production of the higher plutonium isotopes, ^{240}Pu , ^{241}Pu and ^{242}Pu , starts as soon as the ^{239}Pu is formed⁴⁴. In a similar way, ^{238}Pu is produced starting from ^{235}U through a series of neutron captures and decays.

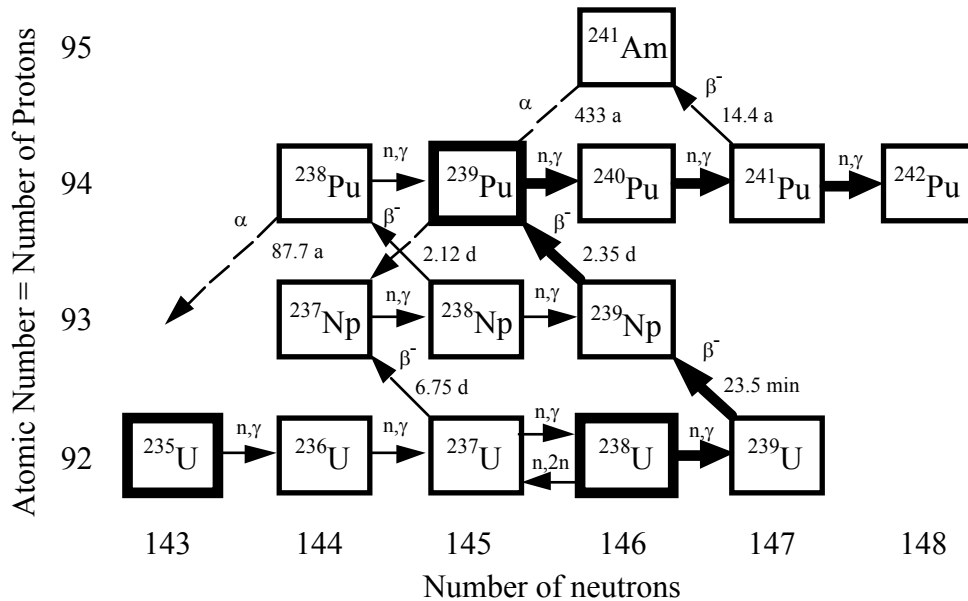


Figure 2.9. Important nuclear processes in a nuclear reactor

In the reactor there is thus a build-up of ^{239}Pu . Part of the ^{239}Pu is then converted into the heavier isotopes of plutonium. This means that the relative amount of ^{239}Pu compared to the heavier isotopes decreases with time as the reactor is operated. This is important, as the relative content of ^{239}Pu should be as high as possible to be optimal for the construction of nuclear explosives.

Figure 2.10 shows how the relative isotopic content of the plutonium changes with time. The “time-scale“ is in this case related to the so called burn-up of the fuel which has the unit $\text{MW}_{\text{th}}\cdot\text{days}\cdot(\text{kgU})^{-1}$, i.e., the amount of energy that has been produced per unit mass of uranium in the fuel⁴⁵. The value to the left 30 000 $\text{MW}_{\text{th}}\cdot\text{days}\cdot(\text{kgU})^{-1}$ represents the approximate mean burn-up of light-water nuclear power reactor fuel as it is removed from the reactor after having been used to optimal fuel efficiency⁴⁶. As we can see, the relative isotopic content of ^{239}Pu

⁴³. This reaction is called an (n,γ) reaction as it also involves the release of γ-radiation.
⁴⁴. These are also formed by (n,γ) reactions.
⁴⁵. 1 $\text{MW}_{\text{th}}\cdot\text{days}\cdot(\text{kgU})^{-1}$ is the same as 1 000 $\text{MW}_{\text{th}}\cdot\text{days}\cdot(\text{tU})^{-1}$, which is the same as 1 $\text{GW}_{\text{th}}\cdot\text{days}\cdot(\text{tU})^{-1}$. All these units can be found in the literature. If MOX fuel is involved the mass of uranium can be replaced with mass of heavy metal, i.e., tHM, which both includes uranium and uranium/plutonium mixtures.
⁴⁶. In this thesis we define the plutonium composition of reactor-grade plutonium as that having a burn-up of 33 000 $\text{MW}_{\text{th}}\cdot\text{days}\cdot(\text{kgU})^{-1}$. This is very close to values to the right in the figure. In recent

decreases with burn-up while the other isotopes increase in relative content. Of course, the absolute content of plutonium increases with time, even though some of it contributes with fission to the energy release in the reactor.

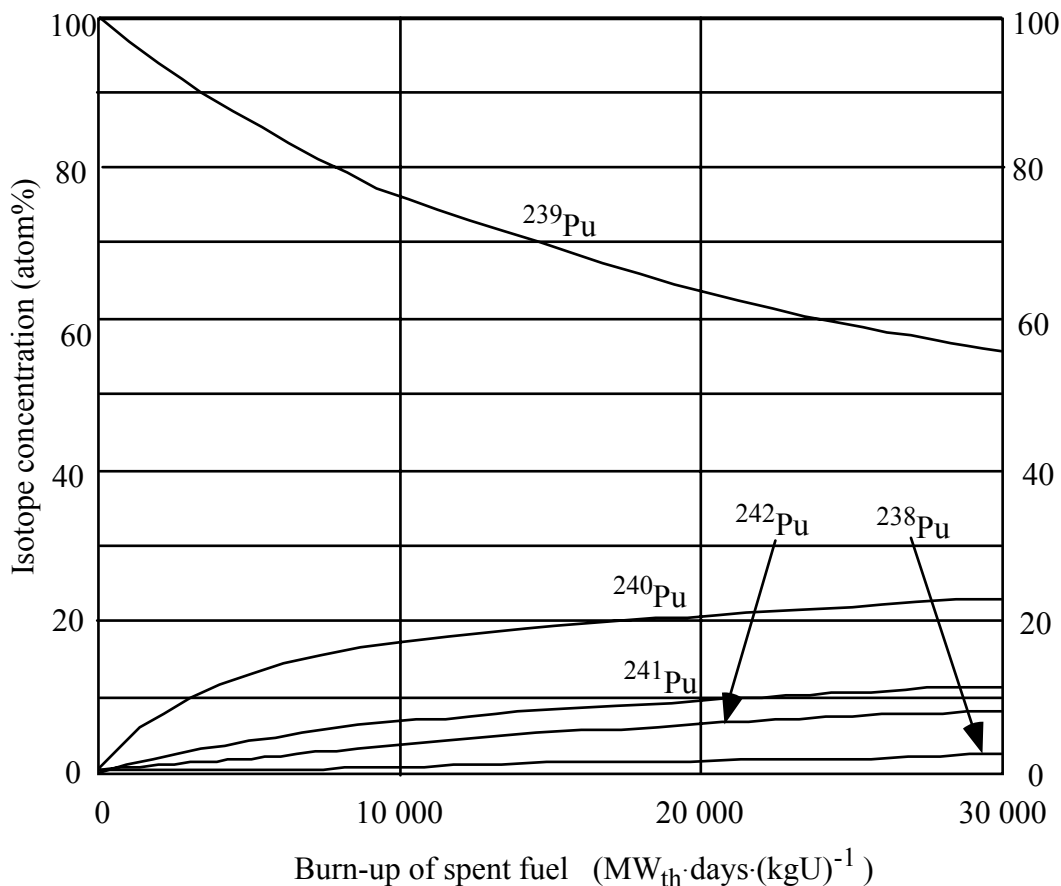


Figure 2.10. The change in plutonium isotope composition with increased burn-up

As will be seen in the next chapter, WGPu is produced so as to obtain as much ²³⁹Pu in relation to the ²⁴⁰Pu isotope as possible, i.e., the fuel should only be irradiated for a short time in the reactor. It is, however, not possible to remove the fuel from the reactor at a too early stage as there is too little plutonium produced and this would result in the reprocessing of very large amounts of spent fuel in order to obtain very little WGPu, albeit of a very high quality. In reality, WGPu is irradiated to contain approximately 93.5% ²³⁹Pu and 6% ²⁴⁰Pu. Such plutonium also contains 0.5% ²⁴¹Pu and negligible amounts of ²³⁸Pu and ²⁴²Pu. This represents a burn-up of about 1 000 MW_{th}·days·(kgU)⁻¹ ⁴⁷. RGPu from a light-water PWR that has been irradiated to a burn-up of 33 000 MW_{th}·days·(kgU)⁻¹ using fuel enriched to 3.25% has an isotopic content of approximately 56.5% ²³⁹Pu, 23.4% ²⁴⁰Pu, 13.9% ²⁴¹Pu,

years, it has become more common to run light-water reactors to a higher burn-up. This is done using fuel of a slightly higher enrichment.

⁴⁷. Gylden & Holm (1974).

4.8% ^{242}Pu and 1.4% ^{238}Pu immediately after being taken out of the reactor⁴⁸.

2.3.1 *Production of Weapons-grade Plutonium*

As discussed in the beginning of this chapter, WGPu is most often produced in military nuclear production reactors⁴⁹. These are most often fuelled with natural uranium, i.e., uranium that has not been enriched. The main reason for this is historical. Access to enriched uranium for fuel, even if it was of very low enrichment, had to compete with the production of WGU. It was also found that to construct a reactor that used natural uranium as fuel and heavy water or graphite as a moderator while allowing easy access to the core for addition and removal of fuel rods while the reactor was running was relatively simple. In order to keep up the capacity for WGPu production it is important that the fuel can be changed while the reactor is running as otherwise the reactor would have to be shut off often due to the short irradiation times needed for optimal burn-up.

Another way to produce WGPu is through neutron irradiation of ^{238}U in a neutron source producing fast neutrons⁵⁰. Such are the conditions in the mantle of a fast breeder reactor (FBR) which contains natural uranium⁵¹. ^{239}Pu is produced from ^{238}U in the same way as described above and so are, in principle, the heavier isotopes of plutonium. However, these have a relatively high probability of undergoing fission so that they do not build up as they do in a thermal reactor. In the mantle of a fast breeder reactor WGPu of high quality is produced⁵². The intention is not normally to use this plutonium in nuclear explosives, but to feed the WGPu back into the breeder. There has, however, already been some concern about French military interest in the world's only existing large-scale FBR⁵³ and a future global energy system relying on a plutonium economy would need very strict control over a large number of FBRs.

Another intense source of fast neutrons would be an eventual future fusion power reactor. The irradiation of ^{238}U would also be possible in such a facility and it would have to be under safeguard control⁵⁴.

In all cases where the WGPu is produced by the irradiation of ^{238}U , the irradiated material has to be chemically reprocessed in order to remove the plutonium for further use in a nuclear explosive. We will not here discuss reprocessing technology, except to say that the information about the technology and

⁴⁸. OECD/NEA (1989, p. 21) and Farmer (1983, p. 17)

⁴⁹. Such reactors are also used to produce tritium for fusion-based nuclear warheads. This is done by the irradiation of targets that contain ^6Li .

⁵⁰. Ordinary reactors that use uranium fuel use moderated thermal neutrons for fission.

⁵¹. For more information about FBRs the reader is referenced to Vendryes (1977), Golan, Leduc & (1989), IAEA (1989C) and IAEA (1990B).

⁵². The plutonium contains 96% ^{239}Pu and 4% ^{240}Pu .

⁵³. See, for example, Albright (1984). The Superphénix is, however, under EURATOM safeguards.

⁵⁴. Still another strong fast neutron source would be the accelerators mentioned in Chapter 8 for the transmutation of high-level nuclear waste. Such accelerators could be used to destroy plutonium, but could just as well be used for fabrication of WGPu.

the materials used are relatively readily available in the literature. It is relatively easy to build and operate a facility for reprocessing compared to building a facility for conventional uranium isotope enrichment. But, to build a large-scale facility would still be quite a task.

2.3.2 *Production of Reactor-grade Plutonium*

The plutonium produced in commercial power nuclear reactors is called reactor-grade plutonium (RGPu). There are, however, many different types of nuclear power reactors and because they are operated differently, the plutonium composition can vary. The main reason for this is that the optimal burn-up for the fuel to be economically used depends on the construction of the reactor, but it is always considerably longer than that used in the production of WGPu. As the relative isotope composition depends on the burn-up, the isotopic composition of WGPu can vary. This is discussed further in Chapter 5 where a scenario for plutonium production in nuclear power reactors is constructed.

Nuclear power reactors are constructed and operated so that fuel economy is optimized. It is most often not possible to change the fuel in the core while the reactor is running⁵⁵.

One important aspect that is often overlooked is that the plutonium isotope composition in the core is not evenly distributed. The figures discussed in this thesis for RGPu composition are average figures for the entire spent fuel. Even if the fuel rods are moved around during refuelling, some parts of the fuel rods will have a plutonium isotope composition with a more favourable plutonium composition for the construction of nuclear explosives⁵⁶. In addition, it is possible to use civil nuclear power reactors for the production of WGPu. As an example, this happened inadvertently in the United States in the early 1970s when leaking fuel rods caused the utility operating the Dresden-2 reactor to discharge the initial core containing an amount of plutonium with 89-95% ²³⁹Pu that would have been enough to construct nearly 100 nuclear explosives (Wohlstetter 1976/77, Wohlstetter 1978). It would be a huge reprocessing task to remove this plutonium, but once again, there would have been a lot of concern raised if Iraq had a large-scale nuclear power programme when the Kuwait crisis started.

2.4 Laser Isotope Separation of Plutonium⁵⁷

As discussed above, technologies for laser isotope separation (LIS) of uranium have been developed during the last few decades. It is important to realize that laser

⁵⁵. This is especially the case for the light-water reactors, as they were constructed to be proliferation resistant.

⁵⁶. Only a part of the core is changed in each refuelling.

⁵⁷. This section relies mainly on Krass (1982), Palmer & Bolef (1984), Krönert et al. (1985), Peuser et al. (1985), Reicher & Salzman (1988).

isotope separation, though originally developed for uranium separation for the civil nuclear fuel cycle, has large implications for the use of plutonium in nuclear explosives. With laser isotope separation it is possible to extract one isotope from an element containing several isotopes close to each other in atomic number⁵⁸. This is the case for plutonium, where one would be interested in increasing the relative content of ²³⁹Pu, but where this is not feasible with conventional isotope separation techniques. The mass difference to the “unwanted“ neighbours ²³⁸Pu and ²⁴⁰Pu is too small to make the process efficient and it would perhaps have to be done in two steps as these isotopes are both heavier and lighter than ²³⁹Pu⁵⁹. It is easier to build a reactor to produce WGPu. If one had a mixture of only ²³⁹Pu and ²⁴²Pu, another “unwanted“ isotope, however, it would be possible to use conventional isotope separation techniques, as they have relative mass difference similar to that of ²³⁵U and ²³⁸U. This is of some interest for the discussion later in this thesis; in Chapter 6 we find a situation where this is the case.

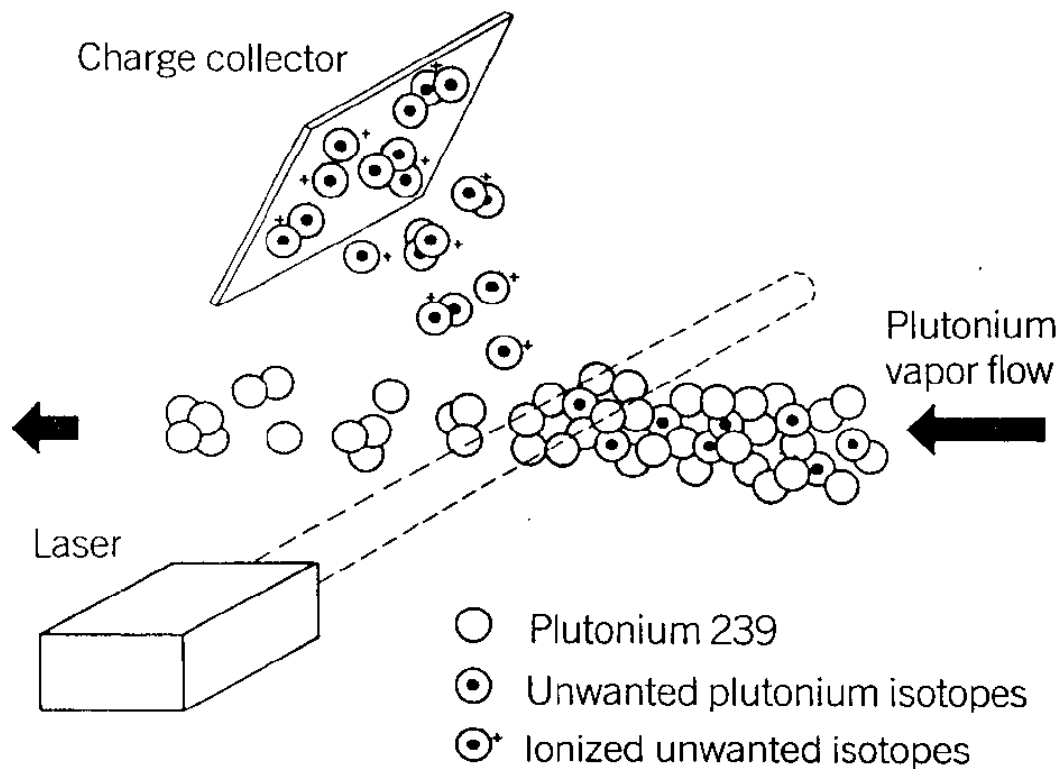


Figure 2.11. Atomic vapour laser isotope separation of plutonium (from Reicher & Salzman (1988, p. 29))

⁵⁸. As discussed in an earlier section, uranium could be enriched using “conventional“ isotope separation techniques because the mass difference between ²³⁵U and ²³⁸U is relatively large.

⁵⁹. This latter problem is actually not too great as the content of ²³⁸Pu in RGPu is not as high as the content of ²⁴⁰Pu (and ²⁴²Pu) and one would only have a slight increase in the absolute content of this isotope in the plutonium. In addition, this isotope has a relative short half-life and while this means that it causes heating of the plutonium, it will “disappear“ in plutonium that is, say, 500 years old.

However, with LIS it is possible to produce WGPu from RGPu⁶⁰. Several countries have been working on the technology for laser isotope separation of plutonium, and the United States has until recently been planning a full-scale production facility for WGPu using an atomic vapour LIS method (Reicher & Salzman 1988, Marshall 1989)⁶¹. The facility, called the Special Isotope Separation (SIS) plant, was to be built at the Idaho National Engineering Laboratory near Idaho Falls. However, with the large-scale cut-backs of the nuclear arsenals giving a large surplus of WGPu, it will now not be needed and it has been cancelled. The plant was intended to convert fuel-grade plutonium from the spent fuel of the United States military nuclear material production reactors⁶². In the early 1980s the United States Department of Energy (DOE), that is responsible for the United States military fissile material production, was interested in processing United States civil RGPu in spent nuclear power reactor fuel to make it into WGPu (Peaslee 1981, Dickson 1981). This caused some concern within the United States civil nuclear industry that has always tried to avoid the military connection as it causes bad publicity for civil nuclear power and these plans were later stopped (Joyce 1981, Norman 1981)⁶³.

Figure 2.11 shows the principles for atomic vapour LIS of plutonium. The method is very similar to the method used for atomic vapour LIS of uranium described above. The main difference is that in the case of plutonium the “unwanted” material is removed and collected on the product collector plate. The ²⁴⁰Pu and ²⁴²Pu atoms can be ionized using light emitted from tuneable dye lasers.

2.5 Definitions and Characteristics of Some Important Nuclear Materials

We would like to end this chapter by summarizing the isotope composition of the different fissile materials discussed in this thesis. In addition, we will here list some characteristics of a few isotopes that are important for the further discussion in the thesis.

In table 2.1 the relative isotopic composition of different types of uranium is presented. As we have stated earlier in this chapter, natural uranium is the material found in ores that are mined. Slightly enriched uranium is used in some types of civil

⁶⁰. One could, in fact, quite easily produce very pure ²³⁹Pu, super-grade plutonium. This is, in fact, a problem concerning verification of arms control and disarmament treaties. If very pure ²³⁹Pu is used in nuclear warheads, the amount of γ and neutron radiation emitted from the nuclear warhead and the detection of the warhead would be much more difficult for a nuclear weapons detection team on an on-site inspection (New Scientist 1989).

⁶¹. Research was started in the United States on the possibility of using LIS for plutonium separation in 1975. As with the LIS programmes for uranium (see section on uranium LIS), molecular LIS was developed at Los Alamos National Laboratory and atomic vapour LIS at Lawrence Livermore National laboratory. The latter technology was chosen in 1982 for further development towards a pilot-scale and full-scale plant (Cochran et al. 1987A, p. 96). However, molecular LIS research continues on a small scale at Los Alamos (Cochran et al. 1987A, p. 133).

⁶². Fuel grade plutonium contains from 7 to less than 19% ²⁴⁰Pu (Cochran 1987A, p. 136).

⁶³. Some controversy was caused a few years later when the United States DOE wanted to use British spent fuel from civil nuclear power reactors instead (Joyce 1984A, Joyce 1984B, Norman 1984A, Norman 1984B).

and military nuclear reactors, but the most common type of uranium in the global civil nuclear programme is low-enriched uranium, which is used in light-water reactors. Higher enrichment levels for low-enriched uranium in light-water reactors are sometimes been used. Enrichment levels of a little above 4% will allow operating the reactors so that the spent fuel has a higher burn-up⁶⁴. Finally we have weapons-grade uranium (WGU), that as we have also stated earlier, is also known as highly-enriched uranium. This definition of the composition of WGU is the one used in this thesis.

Type of uranium	Composition (%)	
	²³⁵ U	²³⁸ U
Natural uranium	0.7	99.3
Slightly-enriched uranium	1.0-1.8	≈98.5
Low-enriched uranium	3	97
Weapon-grade uranium (WGU)	93.5	6.5

Table 2.1. Composition of different qualities of uranium

In table 2.2 the relative isotopic composition of different types of plutonium is presented. Super-grade plutonium is nearly completely pure ²³⁹Pu. Weapons-grade plutonium (WGPu) is the “normal“ material used in nuclear weapons and we will use the composition in this table for our calculations later in the thesis. Fuel-grade plutonium is produced in some nuclear reactors that have a spent fuel burn-up that is lower than that used to produce RGPu but higher than that used to produce WGPu⁶⁵. Reactor-grade (RGPu) is the type of plutonium produced in civil nuclear power reactors.

Type of Plutonium	Composition (%)				
	²³⁸ Pu	²³⁹ Pu	²⁴⁰ Pu	²⁴¹ Pu	²⁴² Pu
Super-grade plutonium	-	99	1	-	-
Weapon-grade plutonium (WGPu)	-	93.5	6	0.5	-
Fuel-grade plutonium	≈7-19% ²⁴⁰ Pu				
Reactor-grade plutonium (RGPu)	1.4	56.5	23.4	13.9	4.8
MOX-grade plutonium	2	42	31	14	11
Fast breeder reactor blanket plutonium	-	96	4	-	-

Table 2.2. Composition of different qualities of plutonium⁶⁶

⁶⁴. It is possible that the reason this is found to be economical is the relatively low cost of enrichment, due to the overcapacity on the enrichment market.

⁶⁵. Fuel-grade plutonium is most often produced in military nuclear reactors that are used to produce tritium. In such reactors the tritium is produced in special targets. As one is not interested in the plutonium for use in weapons the burn-up can be allowed to rise.

⁶⁶. Sources: DeVolpi (1986), Forsström (1982A) Farmer (1983) and OECD/NEA (1989). (cont.) Cochran (1987A) gives the following definitions for different categories of plutonium: supergrade

The composition of reactor-grade plutonium can vary somewhat as discussed earlier in this chapter and in Chapter 5. In this thesis we will rely on the composition defined in this table unless otherwise stated. These values are from OECD/NEA (1989, p. 23) and are based on a PWR light-water reactor, using 3.25% enriched fuel to a burn-up of $33\,000\text{ MW}_{\text{th}}\cdot\text{days}\cdot(\text{kgU})^{-1}$, immediately after unloading from the reactor. MOX-grade plutonium is the plutonium from the first discharge of MOX-fuel using RGPu in the plutonium portion of the fissile material. Fast breeder reactor blanket plutonium is the plutonium that is produced in a blanket of a FBR. As can be seen, the composition is almost identical to that of WGPu.

In table 2.3, on the next page, we have listed some characteristics of various isotopes of interest in this thesis. These characteristics will be used in the discussion in later chapters. For example, the critical masses are important when discussing the construction of nuclear explosives, the half-lives are important when looking at the long term aspects of the nuclear explosives predicament and the spontaneous neutron rate is vital for the discussion of the possibilities of using RGPu for the construction of nuclear explosives.

2-3% ^{240}Pu , weapon-grade less than 7% ^{240}Pu , fuel-grade 7 to less than 19% ^{240}Pu , reactor-grade more than 19% ^{240}Pu .

Isotope	Half-life [years]	Critical mass of bare sphere* [kg]	Spontaneous fission half-life [years]	Spontaneous fission rate [s ⁻¹ .kg ⁻¹]	Neutrons per spontaneous fission $\bar{\nu}_{sf}$	Spontaneous fission neutron rate [s ⁻¹ .kg ⁻¹]	Specific α -activity [TBq.kg ⁻¹]	Specific heat [W.kg ⁻¹]	Surface dose rates for 1 kg sphere*** [mSv.h ⁻¹]
²³⁵ U	7.04·10 ⁸	49	3.6·10 ¹⁷	0.16	2.5	0.39	7.9·10 ⁻⁵	N/A	
²³⁸ U	4.47·10 ⁹	–	8.2·10 ¹⁵	6.8	2.2	15	1.2·10 ⁻⁵	N/A	
²³⁸ Pu	87.7	9/15	4.8·10 ¹⁰	1.16·10 ⁶	2.0	2.3·10 ⁶	644	560	6 580
²³⁹ Pu	24 100	10/15	5.5·10 ¹⁵	10	2.9	29	2.23	1.9	12.1
²⁴⁰ Pu	6 540	40/60	1.3·10 ¹¹	4.2·10 ⁵	2.2	9.3·10 ⁵	8.51	6.8	
²⁴¹ Pu	14.4	12/15	–	–	–	–	4 140**	4.2	
²⁴² Pu	376 000	90/177	6.8·10 ¹⁰	8.05·10 ⁵	2.3	1.85·10 ⁶	0.141	0.1	
²⁴¹ Am	432	114	1.1·10 ¹⁴	500	3.1	1 550	127	114	

* α -phase/ δ -phase for plutonium

** β -decay

*** Sum of X-rays, γ -rays and spontaneous fission neutrons

3. THE CONSTRUCTION OF NUCLEAR EXPLOSIVES

“To know the bomb well, but still continue to hate it...”¹

In this chapter we will review the technologies involved in the development and construction of nuclear explosives². In order to avoid any misunderstanding a few words have to be said about what this chapter is not intended to be. First, this chapter is not based on any classified documentation. It is based entirely on open and readily available sources, sources that can be found by any person or group who starts to investigate the subject³. Second, this chapter is not intended to be a “cookbook for bomb-making”. There is no attempt made to discuss how one would go about to build up a research programme for the construction of a nuclear explosive and or what calculations and testing would be needed⁴. The aim of this chapter is, rather, to give an idea about which technologies are involved for the construction of nuclear explosives so that an interested professional, or informed layman for that matter, can obtain enough knowledge to recognize an overt or covert military nuclear programme when examining pieces of evidence for such activity. This means that in the descriptive parts below, the technology and material used, and a short discussion of why they are used, is emphasized more than the fundamental physical concept behind the choices⁵.

We will in this chapter, in turn, describe the construction of fission nuclear explosives, fusion-boosted fission nuclear explosives, fusion nuclear explosives and then say some words about the construction of third generation nuclear explosives. Finally, we will discuss a subject that is very important for the general discussion in this thesis, i.e., the possibility of constructing nuclear explosives using plutonium produced in nuclear power reactors, so called reactor-grade plutonium (RGPu).

¹. This short notion manifests a dilemma for the researcher who studies the technology of nuclear explosives with the aim of opposing the ultimate use of violence, i.e., the development and use of nuclear weapons. The subject is so full of cutting-edge technology and remarkable technical solutions that it is very easy to be so filled with fascination that the terrible reality that the subject implies can fall from one’s mind. This might show up in some choice of wording in this chapter, although the author has tried to avoid this.

². In this thesis we have, throughout, used the phrase nuclear explosive. The reader who feels “uncomfortable” with this use of terminology may, of course, freely exchange these words for nuclear bomb, nuclear weapon, or nuclear device. The use of terminology is further discussed in Appendix 1.

³. Most of the documents referred to in this thesis have been obtained through the Main Library at the Chalmers University of Technology. If this has failed, seldom as though this has happened, the easiest approach to obtaining a document has been to contact the author or responsible organisation directly. It is interesting to note that the availability of documents can vary from place to place, and possibly from time to time. Meyer et al. (1977) very strongly dispute the often claimed high availability of design information for nuclear weapons. They especially cite the problems they had in obtaining the Los Alamos Primer (Serber & Condon 1943). However, this document arrived to the author on microfiche two weeks after an acquisition form for the publication had been handed in to the Main Library at Chalmers.

⁴. However, many of the documents cited in this chapter give strong indications as to which are the most difficult problems to overcome.

⁵. The fundamental concepts of fission and fusion as well as critical mass, chain reaction etc. are not covered in detail. The reader is referred to the literature, i.e., to Cochran, Arkin & Hoenig (1984) for descriptions of these concepts.

In this thesis we are more concerned about new states or groups, especially in the long-term future, developing the potential to make nuclear explosives, than about existing nuclear weapon states making more advanced nuclear explosives⁶. This means that we will devote more time and space to the construction of fission explosives than to fusion explosives and third generation nuclear weapons. This does not mean that the technologies described are necessarily less advanced. The technology for the construction of nuclear explosives has advanced considerably since the Manhattan Project. In addition, the threshold that has to be crossed in order to obtain a nuclear explosive of any kind involves fission technology. Indeed, fusion explosives are triggered by fission explosives.

There has been a great deal of controversy about the possibility of making nuclear explosives from RGPu. This controversy is discussed towards the end of the chapter and the technical possibilities for such a construction are analyzed. Such possibilities are important to quantify when discussing the possibilities of using the plutonium in a spent fuel repository for the construction of nuclear explosives. The long-term qualities of RGPu in such a repository for the construction of nuclear explosives are discussed in Chapter 6.

3.1 Fission Nuclear Explosives⁷

Fission explosives utilize a chain reaction of nuclear fission reactions in the nuclei of fissile material that has reached criticality. As discussed in Chapter 2, two types of fissile material are almost exclusively used for the construction of nuclear warheads in the present world's nuclear arsenals. These are weapons-grade plutonium (WGPu) and weapons-grade (highly-enriched) uranium (WGU). In addition reactor-grade plutonium (RGPu) is commonly available in the civil nuclear complex and usable for the construction of nuclear explosives. In this chapter we use the composition of these materials that was defined in tables 2.1 and 2.2 in Chapter 2.

Criticality in a nuclear explosive is achieved by allowing the neutron economy of a mass of the fissile material to become such that enough neutrons are allowed to cause new fission reactions so that a chain reaction can be sustained. This mass is called the critical mass. Because the neutron economy depends on several factors, the critical mass of a certain type of fissile material can vary. One important factor is the reflector surrounding the material that forces some of the neutrons that "escape" to return to the mass and another is the density of the material. A compressed amount of fissile material also has a lower critical mass.

It is not enough for a mass of fissile material to reach criticality and sustain a nuclear chain reaction for a nuclear explosion of any force to occur. At this limit we

⁶ The former is often called horizontal proliferation and the latter vertical proliferation.

⁷ The general discussion in this section is based on material from Serber & Condon (1943), Morrison (1950), Magnusson (1955), Magnusson (1956), Selden (1969), Glasstone & Dolan (1977), DeVolpi (1979), Beckett (1983), von Seifritz (1984), Cochran, Arkin & Hoenig (1984), Hansen (1988), Mark (1990), Albright & Hibbs (1991A), Mark (1991), Norman (1991), Albright & Hibbs (1992) and Barnaby (1992).

have nothing more than a nuclear reactor, i.e., if the chain reaction is controlled there can exist a steady-state situation. Instead, the mass has to be what is commonly called supercritical, whereby the chain reaction is clearly divergent. In addition, the fissile material has to be held together for a time long enough so that a considerable amount of the mass undergoes fission.

Fissile material		Density (g·cm ⁻³)	Approximate critical masses (kg)		
			Bare sphere	With 5-10 cm natural uranium shell	With 5-10 cm beryllium shell
WGU		18.8	52	25-20	22-15
WGPu	α-phase	19.5	11	7-5	6-4
	δ-phase	15.8	17	12-7	9-5
RGPu	α-phase	19.4	12	no estimate	no estimate
	δ-phase	15.7	20	no estimate	no estimate
²³³ U		18.5	16	7.5-6.5	7.5-6.5

Table 3.1. Critical masses of important types of fissile material⁸

Let us first study the critical masses of different systems of fissile material. Approximate values for these are presented in table 3.1⁹. As we can see, the critical mass of a bare sphere¹⁰ of WGU is a little over 50 kg. This amount can be decreased by a factor of two to three by the addition of a 5 to 10 cm reflector of natural uranium or beryllium. The critical masses for plutonium are lower. Plutonium at room temperature normally exists in its metallurgical α-phase, where it has a density of approximately 19.5 g·cm⁻³. In this phase the critical mass of a bare sphere of WGPu is about 11 kg. If the plutonium metal is heated to 115°C it undergoes an anisotropic phase change and becomes β-phase plutonium. Such a phase change would mechanically disarm the explosive. At a higher temperature the plutonium enters the δ-phase with a density of approximately 15.8 g·cm⁻³. Plutonium in the δ-phase can be stabilized at lower temperatures by the addition of small amounts of alloys. An addition of one percent (by weight) of gallium is, for example, common in

⁸. Sources: Svenonius & Forsberg (1961), Selden (1969), Lefvert (1973), Paxton (1975), DeVolpi (1979), von Seifritz (1984) and Paxton & Pruvost (1986).

The critical mass of WGU is often given as the mass of ²³⁵U in the material. Here we give the critical mass as that of total mass of WGU with 6.5% ²³⁸U as defined in Chapter 2.

⁹. The values for ²³³U are included in the table for completeness. The possibility of using ²³³U as a fissile material for the construction of nuclear explosives is not discussed in detail in this chapter. It is perhaps enough to state that ²³³U can be produced by the irradiation of thorium-232 (²³²Th) via the intermediate product protactinium-233 (²³³Pa).

There has also been some discussion of the use of ²⁴⁴Cm as fissile material in nuclear explosives (Sahin & Calinon 1985).

¹⁰. A property of a sphere is that for a given volume its surface area is the smallest of all geometrical bodies. The spherical geometry allows the best neutron economy as the fission rate increases with mass, which is proportional to r³ while the leakage depends on the surface area, which is proportional to r² where r is the radius of a sphere.

order to stabilize δ -phase plutonium at room temperature. The critical mass of a bare sphere of δ -phase plutonium is higher than that of α -phase plutonium, about 17 kg.

As we shall see later, there may sometimes be a risk that the plutonium is heated and therefore there may be a risk of it undergoing a phase change. It would be very detrimental to the functioning of a nuclear explosive if such a change occurred unintentionally. It is enough to compare the differences in critical mass to see why. Therefore, if there is a risk of heating, it is better to stabilize the plutonium in its δ -phase and then construct the nuclear explosive using this material, with its known characteristics, as the fissile material. In the table we can also see that the critical mass for plutonium decreases with an added reflector. In fact, as little as 4 kg of WGPu in the α -phase with a 10 cm beryllium reflector becomes critical, even before any compression is applied. As we will later see, the mass of fissile material needed for the construction of a nuclear explosive can be decreased even further if the density of the material is increased by compression.

If we once again look at table 3.1 we see that RGPu has critical masses comparable to those of WGPu. They are in fact a little higher mainly because of the increased content of ^{240}Pu in RGPu. ^{239}Pu has a critical mass of 10 kg (α -phase, bare sphere) as compared to that of ^{240}Pu where the critical mass is 40 kg (α -phase, bare sphere), and therefore the critical mass of RGPu is a little higher than that of WGPu¹¹. We have not included estimates for the reflected critical masses of RGPu but these lie a little above the respective values for WGPu¹².

We have already stated that the critical mass is also dependent on the density of the fissile material. If the material is compacted by compression the density will increase and the critical mass will decrease. The critical mass decreases as the inverse of the square of the density¹³. It has been reported (Skidmore & Morris 1962, Persson & Persson 1963) that by using spherical compression techniques with compression velocities of over 8 000 m·s⁻¹ the density of solid uranium can be increased by nearly a factor of two. 8 000 m·s⁻¹ is however quite a formidable compression velocity. However, at velocities of about 5 000 m·s⁻¹ an increase of about 50% in density is achieved, i.e., the critical mass decreases to 44% of the uncompressed value¹⁴. It is therefore very possible that a competent designer of nuclear weapons could attain criticality with less than one half of the critical masses given in table 3.1¹⁵.

¹¹. If one is to be even more thorough, the relative content of ^{241}Pu and ^{242}Pu also increases in RGPu, even though the amount of the latter is very small. The critical mass (α -phase, bare sphere) of ^{241}Pu is 12 kg and that of ^{242}Pu is approximately 90 kg.

¹². See for example Taylor (1975, p. 413).

¹³. Cochran, Arkin & Hoenig (1984, p. 24).

¹⁴. Selden (1969) states that shock velocities in heavy metals produced by high explosives are approximately 0.5 cm· μs^{-1} , i.e., 5 000 m·s⁻¹. It may be possible to reach higher values, perhaps as high as 10 000 m·s⁻¹.

¹⁵. This discussion would also make plausible the repeated statements that some nuclear weapons have been constructed with less than 2 kg of plutonium. However, using as little fissile material as possible would constrain the attainable maximum yield of the nuclear explosive since it would limit amount of fissile material that could undergo fission. This problem can, however, also be mastered as discussed in the section on boosted fission explosives below.

One can also note that although the critical mass for enriched uranium increases as the relative amount of ^{235}U decreases, it is still considered possible to use the enriched uranium down to levels of enrichment as low as 20% for the construction of nuclear explosives. If 50 kg is the approximate critical mass of a bare sphere of 100% ^{235}U , the critical masses increase to 66 kg at 80% and 105 kg at 60% enrichment. With a beryllium reflector the amounts at 80 %, 50% and 20% enrichment are 21 kg, 75 kg and approximately 250 kg respectively¹⁶.

We can compare the critical masses that are given in table 3.1 with the threshold amounts of fissile material that within the safeguard regimes are considered to be the “approximate quantity of special fissionable material required for a single nuclear explosive device”¹⁷. IAEA has defined these amounts, as 8 kg ^{239}Pu for plutonium ($^{239}\text{Pu} > 95\%$) and 25 kg U ($^{235}\text{U} > 90\text{-}95\%$)¹⁸. These amounts can also be compared with the comparable amounts that the United States requires physical protection for, i.e., 2 kg or more of plutonium and 5 kg or more of ^{235}U (contained in uranium enriched to 20 percent or more)¹⁹. Following the discussion above, the United States values seem to be much more realistic than the IAEA threshold amounts.

As stated above, it is not sufficient for the fissile material to reach criticality in order to obtain a nuclear explosion. The chain reaction has to proceed for a long enough period so that enough fission takes place to release a considerable amount of energy. One usually compares the energy released in a nuclear explosion with the equivalent amount of energy released by a certain mass of the chemical explosive TNT (trinitrotoluene). One kiloton (kt) of TNT is a common unit for the measurement of yields of nuclear explosives²⁰. This represents the approximate yield of the smallest nuclear weapons in the world’s arsenals. The Hiroshima bomb had a yield of 12.5 kt and the Nagasaki bomb 22 kt. A “normal” yield for a modern

¹⁶. It may seem unrealistic to think that one could construct a deliverable nuclear weapon using 250 kg of uranium with 20% enrichment, especially if compression of the core is to be attempted. However, as discussed below, it is not necessary to use a compression technique when using uranium as a fissile material in a nuclear explosive. One can also consider that the Hiroshima bomb, with a total weight of about 4 metric tonnes, is reported to have used a total of 60 kg of 80% enriched uranium. One would, however, need approximately 2 critical masses for such a construction, as there is no compression used.

¹⁷. IAEA (1987B, p 23).

¹⁸. IAEA (1987B, p 23). The IAEA also uses the term significant quantity which it defines as the approximate quantity of nuclear material in respect of which, taking into account any conversion process involved, the possibility of manufacturing a nuclear device can not be excluded. These quantities are used to select accountancy verification goals and are 8 kg plutonium containing less than 80% ^{238}Pu and 25 kg uranium with an enrichment greater than 20% ^{235}U . These values are very similar to the threshold amounts defined by the IAEA, even though the significant quantities take into account unavoidable losses of conversion and manufacturing processes (IAEA 1987B, pp. 23-25).

¹⁹. OTA (1977, p. 143).

²⁰. The majority of the experimental and theoretical values of the explosive energy released by TNT range from 3.8 to 4.6 kJ/g. At one time, there was some uncertainty as to whether the term “kiloton” referred to a short kiloton (976 000 kg), a long kiloton (1 016 000 kg) or a metric kilotonne (1 000 000 kg). In order to avoid ambiguity, it was agreed that the term “kiloton” would refer to the release of 10^{12} calories ($4.187 \cdot 10^{12}$ J) of energy. This represents 4.187 kJ/g of energy release in TNT (Glasstone & Dolan 1977, p. 13).

strategic nuclear weapon is about 100-200 kt²¹.

The explosive energy in 1 kt of TNT is defined as representing $4.187 \cdot 10^{12}$ J of energy. To release this energy with fission requires the fission of $1.45 \cdot 10^{23}$ nuclei assuming the release of 180 MeV of energy per fission²². Let the quantity k represent the number of neutrons available for subsequent fission reactions from any given fission, i.e., k is the difference between total neutron production and total neutron losses. If $k = 1$ the system is just critical. If $k > 1$ we have a supercritical system. One can show that the number of fission reactions occurring during a nuclear explosion is proportional to $e^{(k-1)t/\tau}$ where t is the time taken for the fission reactions to occur and τ is the “neutron generation time”, i.e., the mean time it takes for a released neutron to cause a new fission. If one starts with one neutron and can achieve a value of k of 2, then it would take approximately 53 generations to fission $1.5 \cdot 10^{23}$ nuclei and thus release 1 kt of energy²³. One can show that a reasonable value for τ is about $1 \cdot 10^{-8}$ s²⁴. This would put the total generation time for 53 generations at about $0.5 \mu\text{s}$ ²⁵.

The discussion in the previous paragraph was based on Selden (1969). Mark (1990) carries through a similar discussion in terms of $\alpha = (k-1)/\tau$, which can be described as the rate of fission build-up. Mark states that α , which is zero in a just critical system with $k=1$, may be as high as 10^8 , or a few times 10^8 . Using $k=2$ and $\tau=1 \cdot 10^{-8}$, as we have done, gives an α of $1 \cdot 10^8$, and the total generation time may thus be a few times shorter, i.e., perhaps around $0.2 \mu\text{s}$.

Because the number of fission reactions and thus the energy release increases exponentially, much of the energy release takes place very late in the explosion. In fact, over 99% of the energy release takes place in the last 5 generations of the chain reaction. The release of all this energy is to a large extent transferred to the fissile material itself as kinetic energy that tends to expand the fissile material and thus make the mass subcritical. It is clearly a problem to keep the fissile material critical for a long enough time for a substantial amount of fission to occur. One way of doing this is to surround the material with a tamper, a massive layer of material that has inertial properties that slow the expansion. Heavy materials such as natural uranium or tungsten are chosen. The former, in addition to being heavy, also has good neutron reflecting properties. In addition, the ^{238}U in the natural uranium can contribute to the yield by fission with fast neutrons as discussed in the section on

²¹. The unit megaton (Mt), representing the energy release from the detonation of one million tons of TNT is also used, especially when discussing the yields of larger fusion nuclear explosives.

²². Approximately 200 MeV ($3.2 \cdot 10^{-11}$ J) is released in each fission, but only about 180 MeV is available as explosive energy.

²³. To produce 100 kt would need a further 5 generations.

²⁴. This is referred to as a “shake”. For a bare sphere critical assembly of ^{235}U the generation time is 0.66 shake and for a bare sphere critical assembly of plutonium it is 0.35 shake. It is 2.0 shakes for a ^{235}U spherical core and a thick natural uranium reflector (Cochran, Arkin & Hoenig 1984, p. 24).

²⁵. One can observe that this time is calculated as if one neutron causes one chain reaction. One could imagine that if a large number of neutrons can be released and cause a number of parallel chain reactions this time will be shorter. However, due to the exponential nature of the reactions whereby most of the energy is released in the last few generations only a few generations less would be needed, cutting the time down only marginally.

boosted fission explosives below. Another method for delaying the time until the expansion of the core causes the chain reaction to cease is to increase the density, and therefore decrease the diameter of the core by compression. This allows greater disassembly before subcriticality is reached.

Another problem occurs if the fissile material is not assembled fast enough to ensure that the assembly is complete before the chain reaction starts. There are always spontaneous neutrons being produced in the fissile material, due to spontaneous fission or to (α, n) reactions. There is a possibility that such a spontaneous neutron can start a chain reaction too early. If the chain reaction is started by a “stray” neutron before the optimal time the effect is what is commonly called pre-initiation. The result will be a lower yield, sometimes called a “fizzle”. Below we discuss two types of construction of fission nuclear explosives, the gun-barrel type and the implosion type. The gun barrel type of construction imitates a field gun whose typical muzzle velocities may reach $1\,000\text{ m}\cdot\text{s}^{-1}$. This means $10\ \mu\text{s}$ for each cm of separation and thus it may thus take tens of μs from the time the system is critical until the desired supercriticality is achieved. The second type of construction is the implosion type where a spherical compression of the fissile material is achieved by chemical explosives. Shock velocities in heavy metals produced by high explosives are on the order of $5\,000\text{ m}\cdot\text{s}^{-1}$ ²⁶. This means that it takes $2\ \mu\text{s}$ for each cm of shock wave travel. This is at least 5 times faster than the gun barrel method but it still takes several μs to reach supercriticality. If one compares this with the 0.2 to $0.5\ \mu\text{s}$ that was the time scale of the explosion one realizes that it is important to keep the material in a “neutron free” condition during assembly. This means that if the spontaneous neutron production rate in the material is high, there is a large risk for pre-initiation.

There are some possibilities to minimize the number of spontaneous neutrons generated in the nuclear explosive. There are two main sources of such neutrons. First, we have neutrons that emanate from spontaneous fission. In table 2.3 we have listed the spontaneous fission neutron emission rate of the most important isotopes that are involved in the construction of nuclear explosives. As we can see, the most important emitters of spontaneous fission neutrons are the even isotopes of plutonium: ^{238}Pu , ^{240}Pu and ^{242}Pu . If the relative amounts of these isotopes are kept low in plutonium used in nuclear explosives, the risk for pre-initiation is less. This is the case for WGPu. One of the more important aspects of this problem is that pre-initiation risks are greater for RGPu than for WGPu. The relevance of this is discussed in the section below on using RGPu for the construction of nuclear explosives.

Second, we have so called (α, n) reactions, where an isotope decays with the emission of an α -particle which in turn reacts with the nucleus of some light elements, thereby releasing a neutron. The α -activity of the most important isotopes that are involved in the construction of nuclear explosives are also shown in table 2.3. The easiest way to reduce the number of these neutrons is to make sure that the materials involved are as free from light element impurities as possible.

²⁶. Higher velocities may be achievable.

If we have minimized the number of spontaneous neutrons in the fissile material we have created another problem. How do we get a neutron to start the chain-reaction at the optimal time? One possibility is to wait until a spontaneous neutron starts the reaction, and to hope that the reaction proceeds in such a way that a certain yield is reached. This is not acceptable to designers of nuclear explosives and another method is used, the activation of a neutron source at the optimal time to start the chain reaction. There are two main methods to realize such a neutron source. The oldest method is to design a source so that an α -emitter is mixed with a light element at the optimal time, causing (α,n) reactions. Before this time the materials are physically separated and the α -particles do not reach the light element. Two common materials used in such sources are ^{210}Po as the α -emitter and beryllium as the element in which the (α,n) reactions are caused²⁷. A more modern type of neutron source is the deuterium-tritium (D-T) generator.

Let us now look at schematic diagrams of two possible constructions for a fission nuclear explosive. These are called the gun barrel and the implosion type. In the first type, one subcritical mass of fissile material is shot into another subcritical mass through a tube that has similarities with a gun barrel. In the implosion type a spherical configuration of subcritical fissile material is compressed from all sides by an explosive shock wave emanating from the detonation of conventional explosives. Both types were first developed by the United States in the Manhattan Project during the Second World War. The first nuclear explosive ever detonated, the Trinity Test at Alamogordo in New Mexico on July 16, 1945, was of the implosion type. The bomb dropped on Hiroshima on August 6, 1945, was of the gun barrel type and the bomb dropped on Nagasaki on August 9, 1945, was of the implosion type. The reason for developing two types of construction was the pre-initiation problems caused by the neutron background in the fissile material, the problem being greatest with plutonium. The gun barrel type of construction, although simpler to realize than the implosion type, was not thought to allow fast enough assembly to avoid pre-initiation if plutonium was used as fissile material. Thus, the Alamogordo and Nagasaki nuclear explosives used plutonium as fissile material and the Hiroshima explosive was constructed with WGU^{28,29}.

A schematic diagram of a gun barrel nuclear explosive is shown in figure 3.1³⁰.

²⁷. An interesting and quite recent revelation about the Windscale accident in 1957 was that a major radiation problem was due to the release of ^{210}Po that was being produced by irradiation of bismuth targets in the fire-ridden reactor (Pearce 1983A and Pearce 1983B). This ^{210}Po was to be used for neutron initiators in the British nuclear weapon programme and the release of the isotope was, due to secretiveness, not announced at the time of the accident. The ^{210}Po -Be neutron source has to be changed periodically as ^{210}Po has a half-life of only 138 days.

²⁸. This can also be seen in the geometrical shape of the Hiroshima and Nagasaki bombs. The Hiroshima bomb, called Little Boy, was elongated and the Nagasaki bomb, called Fat Man, was spherical in its construction. These shapes can be compared with the shape of the schematic constructions in figures 3.1 and 3.2.

²⁹. As discussed above it is possible that the uranium used in the Hiroshima nuclear explosive was enriched only to about 80%.

³⁰. This diagram and the subsequent diagrams of an implosion type fission explosive and a fusion explosive are indeed schematic. There has been no attempt made to make the parts of the devices proportional to their actual size in a real nuclear explosive.

We can see two subcritical masses, one of which can be shot into the other through a tube by the detonation of a charge of a conventional explosive. This material has to be a material with a low spontaneous neutron background as the assembly time for a gun-barrel device is of about 5 to 10 times slower than an implosion device, as discussed above. This means that WGU is the material of choice, as indicated in the figure.

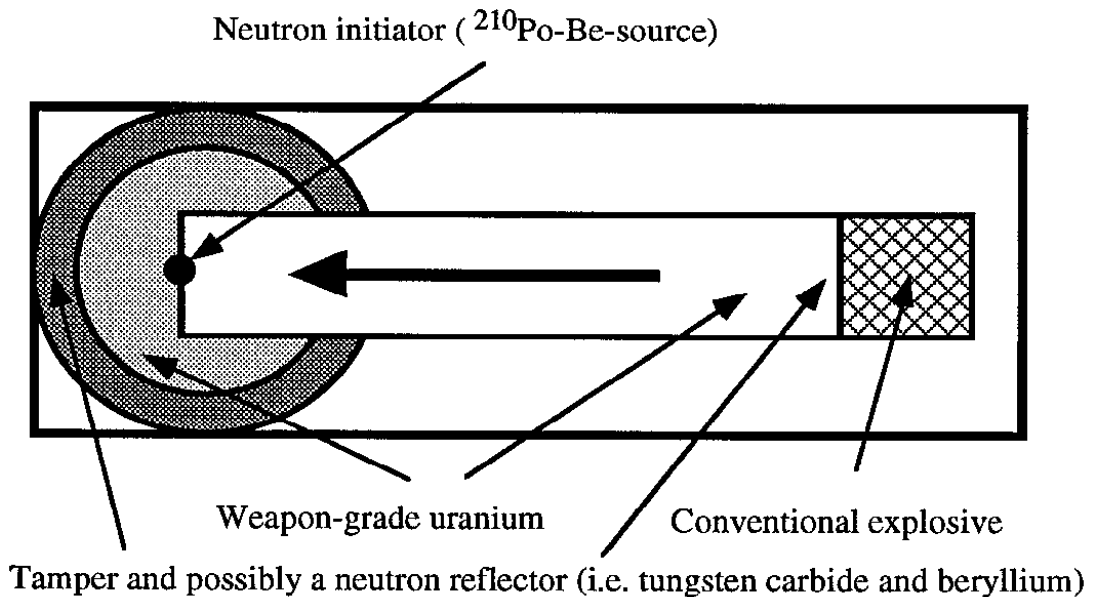


Figure 3.1. Schematic description of a nuclear explosive of the gun barrel type

The stationary mass of WGU is surrounded by a tamper to slow down the expansion of the exploding fissile material. This tamper is made out of a material with high density to have a high inertia. A material possible to use is natural uranium. However, if one is very concerned about the spontaneous fission neutron background in ^{238}U , which is higher by a factor of 20 than that of ^{235}U , one could choose another material, i.e., tungsten carbide.

The tamper can be combined with a neutron reflector made of, for example, beryllium. If natural uranium is used as a tamper it is also effective as a neutron reflector.

As the two subcritical masses of fissile material collide, a neutron generator of the ^{210}Po -Be type is activated through the mixing of the materials.

As we discussed above, the gun-barrel type of nuclear explosive is not effective to use if there is a high spontaneous neutron background as the assembly time is relatively long. It is possible to achieve much shorter assembly times if the implosion type of nuclear explosives construction is used. A schematic diagram of such a device is shown in figure 3.2.

An implosion construction uses a spherical configuration. There is an outer layer of conventional explosives that are used to compress the central parts of the construction. In order to do this effectively, use is made of so-called shaped charges

which direct the detonation wave in a certain direction, in this case inwards. This is done by combining slower and faster detonating explosives in “lenses” in such a way that the resulting explosive shock wavefront is spherical and converging inwards. The conventional explosives are, of course, tampered on the outside to restrict outward motion of the explosion.

In addition, the inward compression has to be as uniform as possible. Detonators, in numbers up to and even exceeding 90, are placed all around the outside of the device in a symmetrical fashion. These have to be triggered as closely together in time as possible. This places great importance in the design of the triggering circuit and there is a need both for fast switches and for high power and fast detonation capacitors that can deliver energy to the detonators very rapidly. A common type of switches are krytrons³¹. In order to even out differences in the velocity and position of the inward moving shock wave one can also place thin and light shells, i.e., made from aluminium, between the layers of explosives.

Inside the layer of conventional explosives are the tamper and the neutron reflector, as in the gun-barrel type of construction. In this case it is not a problem to use natural or depleted uranium as a tamper³². The implosion device allows much faster assembly and in addition, the spontaneous neutron background due to spontaneous fission neutrons in the plutonium of the core is anyway comparatively high anyway, even in the case when WGPu is used.

Inside the neutron reflector, which can be made of beryllium is a hollow space³³. The core is “levitated” inside this space. The space is to allow for the gathering of inward momentum of the tamper/reflector before it hits the core. This type of construction greatly increases the compression velocity of the shock wave in the core.

The core itself can either be a pure WGPu core or a pure WGU core or a combination of these materials³⁴. The centre of the core is hollow. First, this allows more efficient compression of the core and second, this allows the use of “boosting” as discussed in the next section. The plutonium core is plated with a thin layer of nickel, silver or gold to avoid corrosion problems.

³¹. The trade of these small switches is strictly controlled and every now and then attempts of covert acquisition by threshold countries is disclosed. See, for example, Newsweek (1985).

³². The tamper made of natural uranium of course also acts as a reflector.

³³. Beryllium is in this case a moderating reflector, i.e., it lowers also lowers the energy of the neutrons so that they are at energies where the fissile ^{239}Pu and ^{235}U have high fission cross sections.

³⁴. In the latter case, the faster-fissioning plutonium is placed inside a shell of WGU to allow more efficient use of the neutrons released by its fission. The use of a composite core may seem unusual as the “normal” situation for a country acquiring nuclear weapons would be to produce either WGU or plutonium. However, after the Second World War, this type of construction did allow the United States to make more effective use of its relatively large amounts of available WGU, compared to WGPu. In addition, a relatively large amount of uranium can be assembled for a high-yield fission device, i.e., for plutonium the amount, by mass, that can be used is less because of problems with criticality. This means that if a fission nuclear explosive with as high a yield as possible is to be constructed, WGU should be used. The addition of some plutonium would then allow even more effective utilization of the uranium. Such developments led to the November 1952 test of the Mark 18 Super Oralloy Bomb that yielded 500 kt (Rosenberg 1983 and Hansen 1988, p. 36).

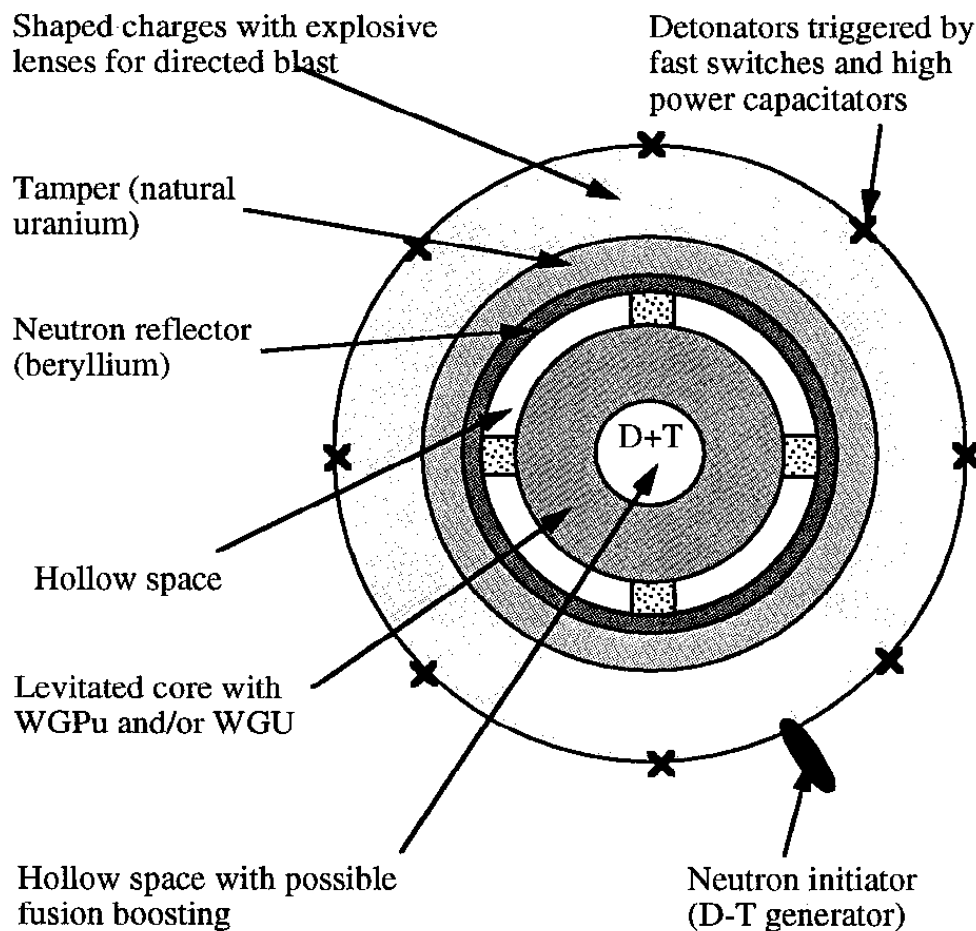


Figure 3.2. Schematic description of a nuclear explosive of the implosion type

In this construction another type of neutron source for the initiation of the chain reaction, a deuterium-tritium (DT) accelerator, is shown. This type of source is often called an “urchin” because of its shape which is slightly elongated. In this type of neutron source ionized deuterium atoms are accelerated into a tritium target thereby causing a fusion reaction with the release of fast 14.1 MeV neutrons. At the right moment this accelerator is triggered and a stream of neutrons are injected into the supercritical core.

As we have mentioned earlier, the implosion type of construction does allow the use of RGPu as fissile material. The drawbacks that are due to the high spontaneous neutron background from spontaneous fission of the even-numbered plutonium isotopes can partly be overcome by the relatively fast assembly times that are possible with this type of construction. We will return to this subject later in this chapter.

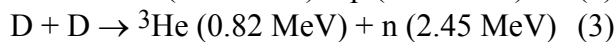
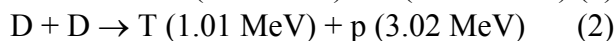
We have in this section only discussed the main components of the exploding device. In addition there are other components that are vital to the functioning of the explosive in a nuclear weapon system. There has to be a power supply, a timing circuit, an arming system and a fusing system. The latter regulates the detonation of

the nuclear weapon, for example at which height it is to explode if dropped as a bomb. There is often some sort of security feature included in the arming system of the explosive that hinders the detonation of the nuclear weapon without the proper authority³⁵.

3.2 Fusion-boosted Fission Nuclear Explosives

In the previous section we saw that in the implosion type of construction of a fission explosive the core can be hollow. We mentioned that this allows the compression of the core to proceed at a higher rate, but also that this technology allowed the construction of a fusion-boosted fission nuclear explosive.

Let us first study some fusion reactions, i.e., the binding together of two light nuclei accompanied by the release of large amounts of energy. These reactions, however, also require the input of relatively large amounts of energy in order to occur. Fusion reactions take place at extremely high temperatures and pressures, but such conditions can be reached in the centre of an exploding fission explosive. The most common fusion reactions involve two isotopes of hydrogen, deuterium (D) which is another name for ^2H and tritium (T) which is another name for ^3H . The reactions are:



The DD reactions proceed with approximately equal probability in each of the two ways. Of the reactions the DT reaction is more important than the DD reactions because it occurs at more easily realizable temperatures and pressures³⁶.

If a mixture of deuterium and tritium are put in the hollow in the core of a fission explosive, fusion reactions will occur as the device explodes. However, the amount of these materials that are possible to put in this hole is relatively small and the fusion reactions contribute a relatively small part of the total energy released. More important are the fast neutrons released by the fusion reactions. These can increase the number of neutrons available for fission reactions in the core by collisions with the nuclei of the fissile material. It is possible that these additional neutrons can raise the value of α as discussed in the previous section from a value of around 2 to perhaps as much as a value of 10. This would decrease the time needed to generate the 53 generations of fission to reach 1 kt to as low as 0.05 μs .

In addition, because the neutrons possess a high energy, 14.1 MeV, they will

³⁵. These are called permissive action links (PALs). In this context we can also mention that much work has been put into finding conventional explosives that are tolerant to shock and fire from an accident. An explosive that is sometimes mentioned in this context is triaminonitrobenzene (TATB) (Hansen 1988, p. 32 and FOA-Tidningen 1981).

³⁶. The temperatures reached in a fission nuclear explosive are about 10^7 to 10^8 K. The DT reaction occurs at temperatures of about $7 \cdot 10^7$ K while the DD reactions require temperatures of about $6 \cdot 10^8$ K. At the same temperature the probability for a DT reaction is approximately 100 times the probability of a DD reaction.

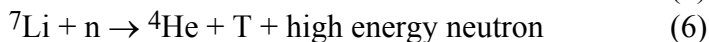
cause fission in the ^{238}U in a natural or depleted uranium tamper/reflector. ^{238}U has a high cross section for fission by high energy neutrons.

The total result of the fusion “boosting” of a fission nuclear explosive can increase the yield by approximately a factor of two to five compared to a similar, but un-boosted, construction.

Let us now study how one could, in practice, construct a boosted fission nuclear explosive. Deuterium and tritium are gases at room temperature and pressure. It may be possible to pressurize the hollow compartment so that more gas can be included in the explosive in order to increase the number of atoms that may undergo fusion. It is, however, not practical to keep the gases at a high enough pressure or to cool them enough so that they are in a liquid state. It is difficult enough to seal a container tight in order to avoid the leakage of such small molecules even at low over-pressures and cooling by refrigeration would require constant monitoring³⁷.

There is, however, another possibility that would make the construction of the boosting component simpler. If the deuterium is combined with lithium in the form of lithium deuteride (LiD), which is a solid chemical compound at room temperature, it is possible to at least have the deuterium in solid form in the core. The DT reaction can thus take place between the deuterium in the LiD and the tritium gas.

Natural lithium is next to hydrogen and helium the lightest element and consists of two isotopes, ^6Li (7.5%) and ^7Li (92.5%). The lithium can contribute to the energy release. There are mainly three relevant nuclear reactions:



The ^6Li reaction (4) produces tritium that can undergo the DT reaction (1) with the deuterium in the LiD³⁸. The resulting net thermonuclear reaction is therefore:



The incoming neutrons in the ^6Li reaction (4) can be neutrons from the fission in the core while in the ^7Li reactions (5 and 6), high energy neutrons from fusion are

³⁷. The first United States thermonuclear fusion test “device” did use liquid deuterium and depended on the DD-reaction. The Mike Device, detonated on November 1, 1952, weighed between about 65 tonnes and was cooled by the largest experimental cryogenic device ever constructed. The yield of the device was 10.4 Mt.

³⁸. It seems as though in principle ^6LiD could be used on its own in a boosted fission explosive. In fact, tritium is to a large extent used. Tritium has a relatively short half-life of 12.3 years and therefore needs to be replenished on a regular basis. There has been quite an intense discussion in the United States about how tritium production for nuclear production can be continued when the production reactors have had to be shut down. This indicates that tritium is an important component and that there is a role which LiD can not fill on its own. This might be due to several reasons. First, it is possible that the two-step reaction that needs to take place in the ^6LiD is not fast enough to release neutrons to the fissionable material in the core. Second, the selectable yield option with the bleeding in of a known amount of tritium gas, as described below, requires tritium. Third, the enhanced radiation (neutron) explosive, as described in the next section, is based on the principle that as high and fast neutron flux as possible is produced and it might be advantageous to use tritium in this context.

needed. Because of this, as well as the bonus in the tritium production, and because the cross-sections for the ${}^7\text{Li}$ reactions were not fully known at first, ${}^6\text{Li}$ was considered more important than ${}^7\text{Li}$ ³⁹. Therefore effort was put into isotope separation of lithium so that as pure ${}^6\text{Li}$ as possible could be produced⁴⁰.

If ${}^7\text{Li}$ is used in the core, the high-energy neutrons from the third reaction (6) can cause fission in the ${}^{238}\text{U}$ in a uranium tamper. For such reactions, however the high-energy neutrons from the DT reaction are more important. The DT reaction produces 14.1 MeV neutrons and these neutrons can, in addition to contributing to the fission in the core, cause fission in the ${}^{238}\text{U}$ in a natural or depleted uranium tamper⁴¹. This contribution to the energy release of a boosted fission explosive can be substantial. If a beryllium reflector is used inside the natural or depleted uranium tamper this can also increase the fast neutron flux in the tamper as the beryllium can act as a neutron multiplier⁴².

The use of fusion boosting in a fission nuclear explosive also gives a relatively simple possibility for varying the yield of the explosive without making changes in the amounts of fissile material in the core. This can be done either by inserting different “boosting cartridges” into the core of the fission explosive or by bleeding in an amount of tritium gas into a LiD matrix in centre of the explosive. This latter technique would in principle allow a sort of “dial-a-yield” construction.

Let us shortly, before proceeding on to the fusion nuclear explosives, discuss some of the more important development tools for nuclear explosives. First, we have the computer. Many calculations and simulations can be done that can later be used in the construction work. The use of computers was very important for the development of the United States fusion nuclear explosives and the United States still has export controls for its most powerful computers to threshold countries. Second, we have flash X-ray machines. These allow the taking of photographs of

³⁹. It has been stated that an underestimate of the probability the ${}^7\text{Li}$ reactions was the cause of the serious underestimate of the yield Bravo test of the Shrimp fusion nuclear explosive that was done by the United States at Bikini on March 1, 1954. The yield was two and a half times the calculated yield, i.e., 15 Mt instead of 6 Mt. This meant that the fallout from the test was therefore larger than anticipated. This, in combination with an unexpected shift in winds caused contamination of the Japanese fishing vessel Fukuryu Mary (Lucky Dragon) and forced the evacuation of several surrounding atolls. The test led to the contamination, to some extent, of the whole north part of the Marshall Islands (Hansen 1988, pp. 65-66).

⁴⁰. A lithium enrichment facility is described in Cochran (1987B, pp. 74-75). It is interesting to see that research on lithium enrichment also took place in Sweden during the 1950's and 1960's, partly at the Swedish National Defence Research Institute (Lundén, Christofferson & Lodding 1959, Lundén 1963, Collén 1964A, Collén 1964B). At this time Sweden had a had a covert nuclear weapons development programme (see Chapter 4).

⁴¹. ${}^{238}\text{U}$ has a high threshold energy at about 1 MeV for the neutrons that can cause fission and therefore high-energy neutrons are needed. The mean energy of fission neutrons is on the order of 2 MeV, but the neutrons continuously lose energy in collisions. See also the discussion of the moderating effect of beryllium in the next note. In beryllium, the fission neutrons very soon lose their energy so that it falls below 1 MeV.

⁴². The reaction is ${}^9\text{Be} + n \rightarrow {}^8\text{Be} + 2n$. This bonus is in reality somewhat less as the beryllium also acts as a moderator and therefore lowers the energy of the fast neutrons. This means that some may fall below the fission energy threshold of about 1 MeV for ${}^{238}\text{U}$. Thus, to be efficient, the beryllium reflector has to be optimized in thickness so that it “reflects” thermal and slow neutrons but does not to a large extent moderate fast neutrons.

very fast events through solid objects. These are vital for the development of shaped charges for implosion fission explosives. In fact, tests of the complete implosion process can be conducted using replacement materials for the fissile material.

3.3 Fusion Nuclear Explosives⁴³

In a fusion nuclear explosive, which has also been called a hydrogen or a thermonuclear explosive, most of the explosive energy comes from fusion reactions. While a pure fission nuclear explosive might have a yield of about 20-40 kt and a boosted fission explosive about two to five times this value, there is practically no upper limit on the yield of a fusion nuclear explosive. The largest nuclear explosive ever detonated was the Soviet 58 Mt test of October 30, 1960. The reason for the lack of upper limit is the way fusion nuclear explosives are constructed. A schematic drawing of a fusion explosive is shown in figure 3.3.

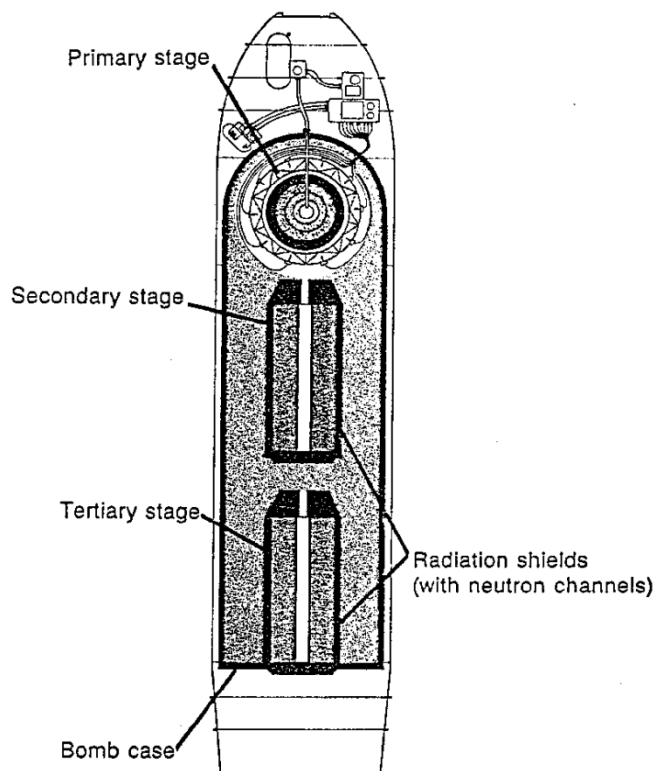


Figure 3.3. Schematic drawing of a fusion nuclear explosive (from Hansen (1988, p. 22))

⁴³ The discussion in this section is very brief. More details can be gained from reading Ridenour (1950), Rydberg (1950), Rydberg (1954), York (1976), Morland (1981), DeVolpi (1981), Winterberg (1981), Cochran, Arkin & Hoening (1984), von Seifritz (1984) and Hansen (1988).

As can be seen in the figure, the fusion explosive consists of a fission or boosted fission explosive as a trigger and then a separate (or several separate) fusion part(s). The use is made of the soft X-rays that are produced in large amounts in the fission trigger. Compression of secondary is due to recoil from X-ray ablation of the casing. Neutrons are led to a “spark plug” of fissile material in the centre of the LiD in the fusion compartment, where then fission occurs producing neutrons that can start to generate tritium in the LiD. The compression of the LiD and the spark-plug occurs earlier than the fission because of the difference in velocity of the soft X-rays and the neutrons. The LiD is now consumed by fusion reactions. This fusion stage can be repeated a number of times, thus, in principle, making possible an infinitely large explosion⁴⁴. Figure 3.3 has such two fusion stages.

In addition, the outer casing can contain natural or depleted uranium and the ^{238}U in this material will be fissioned by fast neutrons. The resulting nuclear explosive is thus a fission-fusion-fission explosive.

3.4 Third Generation Nuclear Explosives⁴⁵

If the fission nuclear explosive was the first generation of nuclear explosives and the fusion nuclear explosive was the second generation of nuclear explosives, then the development of nuclear explosives that enhance one or more of the characteristics of the nuclear explosion can be said to be the third generation of nuclear explosives. These can be enhancement of some type of radiation, or blast.

The most well-known type of third generation nuclear explosive is the enhanced neutron radiation explosive, known as the neutron bomb. Such explosives have been deployed in United States artillery shells and short-range missiles. In this type of nuclear explosive every care is taken to maximize the output of fast neutrons from fusion reactions. This means that the amount of fissile material in the core is as low as possible; tritium is used to a large extent to maximize the number of DT reactions and there is no uranium used as a tamper.

Other third generation nuclear explosive concepts that have been considered are the X-ray laser pumped by a nuclear explosive for use in strategic defence systems in space, nuclear explosives that produce microwave energy that from space could be directed downwards to destroy unshielded micro-electronics, nuclear explosives that from space produce large electromagnetic pulses (EMP) that on the Earth's surface would destroy unshielded electronics and nuclear explosives that would be robust enough for earth penetration in order to explode underground and destroy

⁴⁴. One could think that such a device could be “a doomsday machine” that could eradicate all living beings on Earth. However, serious discussion, if one can call it that, of such a device also included a large “contamination” part of, for example, cobalt that when irradiated would produce fallout that would spread around the world (Arnold 1950). The explosion in itself, though perhaps very large, would only have “local” effects.

⁴⁵. The discussion in this section is very brief. More details can be gained from reading Kaplan (1978), Kaplan (1981), Scoville (1982), Cohen (1983), Cochran, Arkin & Hoenig (1984), Morrison (1984), Tsipis (1985), Taylor (1986), Taylor (1987), Hansen (1988) and Fenstermacher (1991).

subterranean command centres.

3.5 Using Reactor-grade Plutonium as Fissile Material for the Construction of Nuclear Explosives

Statements are not seldom made that reactor-grade plutonium (RGPu) is not suitable for use in nuclear explosives. Such statements are often misinterpreted as declaring that RGPu can not at all be used for this purpose, which is definitely wrong. We shall in this section discuss the possibilities of using RGPu for the construction of nuclear explosives.

Historically it has been a convenient and generally accepted "fact" within the civil nuclear establishment that RGPu produced in the normal operation of a civil nuclear power reactor is useless for the production of nuclear explosives. It was believed that the high number of spontaneous fission neutrons in RGPu would pre-empt the nuclear explosive causing it to fail.

The United States Atomic Energy Commission dissociated itself from this standpoint already in 1952⁴⁶. Already in 1962 the United States tested a nuclear explosive that used as fissile material plutonium of reactor-grade quality. This was first publicly announced in 1971 in connection with an IAEA safeguard conference⁴⁷. The same year J. Carson Mark, then director of the theoretical division of the Los Alamos National Laboratory, a nuclear weapons construction laboratory, stated that "...the old notion that RGPu is incapable of producing nuclear explosions ... is dangerously exaggerated"⁴⁸. In a 1974 report from the Swedish National Defence Research Institute the possible yields of nuclear explosives constructed using RGPu are discussed in detail⁴⁹. Since then, a number of analyses have been published that discuss this question⁵⁰. However, even though the "uselessness" of RGPu for the construction of nuclear explosives for long has been exposed as a myth, it is still an often repeated standpoint today.

Between 1976 and 1980 the Carter administration in the United States had a policy on civil nuclear issues that included opposition to reprocessing of spent nuclear fuel and the recycling of RGPu, mainly because of the risk of nuclear proliferation. The United States wanted the rest of the world to follow its example but there was foreign opposition to the new policy⁵¹. At this time the question of the possibility of using RGPu in nuclear explosives was once again brought to the fore. Material was collected by scientists at Lawrence Livermore National Laboratory and

⁴⁶ Taylor (1973, p. 181).

⁴⁷ SKI (1986) as sent in a letter to Lars Nordström.

⁴⁸ Mark (1971).

⁴⁹ Gyldeén & Holm (1974).

⁵⁰ See, for example, Meyer, Loyalka & Williams (1975), Fleck (1976A), Fleck (1976B), Locke (1976), Sahin (1976B), Nelson (1977), Meyer et al. (1977), Sahin (1978), DeVolpi (1979), Lovins (1980), Sahin & Ligou (1980), Sahin & Yalçin (1980), Sahin (1981), von Seifritz (1981), DeVolpi (1982A), von Seifritz (1984), Bloom (1985), DeVolpi (1986), Mark et al. (1987) and Mark (1990)

⁵¹ Many European countries, as well as Japan, at this time had advanced plans for plutonium recycling as MOX fuel and in fast breeder reactors.

in 1976 both domestic and foreign specialists from the civil nuclear establishment were informed of the risks that RGPu could be used in nuclear explosives⁵². In addition, in September 1977 a spokesman for the United States DOE Energy and Research Development Administration (ERDA) once again confirmed that the United States detonated a nuclear explosive, using plutonium of the same isotope composition as in RGPu, in 1962⁵³. The spokesman said "that a test was conducted using reactor-grade plutonium and that it successfully produced a yield".

Let us now take a look at the main difficulty encountered in the construction of a nuclear explosive using RGPu as fissile material, i.e., the relatively high spontaneous neutron background that may cause pre-initiation of the explosive. This would be the case if the chain reaction started so early that the optimal degree of supercriticality was never reached.

We found in Section 3.1 that in a supercritical system, the number of neutrons, the rate of fission and the release of energy all increase exponentially as $e^{\alpha \cdot t}$ where α is the rate of fission build-up. We found that α could be as high as $2 \cdot 10^8 \text{ s}^{-1}$ to $10 \cdot 10^8 \text{ s}^{-1}$, the latter being the case in a boosted fission device. This meant that the time needed for the chain reaction to reach a yield of 1 kt was on the order of 0.2 μs to 0.05 μs . We also noted that the extra time needed to reach 10 kt or 100 kt was marginal due to the exponential increase in magnitude.

We also discussed the possible compression velocities that could be achieved in a core of a fission nuclear explosive and found that these could be as high as $5\,000 \text{ m}\cdot\text{s}^{-1}$ to perhaps $10\,000 \text{ m}\cdot\text{s}^{-1}$. If we use a value of 0.2 μs for the explosion time and $5\,000 \text{ m}\cdot\text{s}^{-1}$ for the compression velocity, the fissile material would only be compressed 1 mm during this time. Clearly the compression has to be allowed to continue for some time before the chain reaction is started.

Recently, J. Carson Mark, who was cited above, in a report has discussed the explosive properties of RGPu (Mark 1990). Starting from a quotation from Oppenheimer made just after the Trinity explosion, as cited in Wohlstetter (1978) and the discussion in the Los Alamos Primer (Serber & Condon 1943) he argues as follows.

In an approximate calculation valid for a small degree of supercriticality, the efficiency of a nuclear explosion is proportional to α^3 of the α value when the disassembly process gets well under way. In a core with a mass of 10 kg this will take place when the value of $\alpha \cdot t$ has reached between 40 and 45⁵⁴. If the core is highly supercritical when the chain reaction starts, i.e., if α is on the order of

⁵². At these briefings charts were presented by Robert W. Selden at Lawrence Livermore National Laboratory. These appear to have been entitled Reactor Plutonium and Nuclear Explosives and have been cited in various articles. They are however unpublished and the author has not been able to gain access to them.

A series of briefings for United States and foreign nuclear specialists were held by the United States Energy Research and Development Administration (ERDA) at a meeting of the Atomic Energy Forum/American Nuclear Society (Nuclear News 1976 and Wohlstetter 1978, p. 38).

⁵³. Draeger (1977), Gillette (1977A), Gillette (1977B), Gillette (1977C), Ingersoll (1977), Gillette (1978, p. 8), Wohlstetter (1978, p. 38) and Hill (1980, p. 55).

⁵⁴. This corresponds to 40 to 45 generations in the chain reaction, where 58 generations are needed to reach 100 kt.

$2 \cdot 10^8 \text{ s}^{-1}$, the time to reach a value of 45 would be so short that the degree of supercriticality, i.e., α , would not change during this time. However, if the chain reaction started much earlier there could be a larger change in α during the corresponding period. In this case one has to consider $\int \alpha \cdot dt$ instead of $\alpha \cdot t$ and the explosion value for α would be the value when $\int \alpha \cdot dt = 45$.

The smallest yield that will be the result of a nuclear explosion, i.e., the “fizzle” yield, is the one that would be the result if the chain reaction starts just as the core reaches criticality. The more rapidly α increases, the larger would be the α value when $\int \alpha \cdot dt = 45$. This means that the faster the assembly proceeds, the larger the “fizzle” yield for the explosive because the efficiency of a nuclear explosion is proportional to α^3 .

The yield of the nuclear explosion thus to a large extent depends on the degree of supercriticality of the core when the chain reaction starts. If the chain reaction is the result of reactions from spontaneous neutrons, its starting time is a matter of probabilities. Mark uses the following figures as quoted by Oppenheimer of the probability that the Fat Man nuclear bomb dropped on Nagasaki explosion would reach various yields.

Nominal ($\approx 20 \text{ kt}$ ⁵⁵): 0.88

Above 5 kt: 0.95

Above 1 kt: 0.98

Fizzle (\approx “not much less than 1 000 tonnes”) to 1 kt: 0.02

He also states that the probability of reaching the nominal yield would vary with the neutron background, with everything else constant, in such a way that the probability of reaching a nominal yield with twice the neutron background would be $(0.88)^2$, and with three times the neutron background would be $(0.88)^3$, and so on. Here we leave Mark's discussion.

If we examine the neutron source of WGPu and RGPu we find that the neutron source for the former is about $56\,000 \text{ neutrons} \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$ and the latter is about $340\,000 \text{ neutrons} \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$, i.e., a factor 6.1 of difference higher for RGPu⁵⁶. This would lead to the following approximate probabilities to reach the above yields:

Nominal ($\approx 20 \text{ kt}$): $(0.88)^{6.1} = 0.46$

Above 5 kt: $(0.95)^{6.1} = 0.73$

Above 1 kt: $(0.98)^{6.1} = 0.88$

Fizzle (\approx “not much less than 1 000 tonnes”) to 1 kt: 0.12

Advanced compression and boosting will not to a great extent affect these probabilities relative to one another. However, the yields that will be the result of the explosion will be higher, even for a “fizzle”, as the nominal yield for such advanced constructions may be a factor 2 to 5 of the nominal yield of the Fat Man bomb.

We have thus found that probabilities determine the energy yield of a nuclear explosive and the reliability with which it will reach that yield. We have also found

⁵⁵. The Nagasaki explosion had a yield of 22 kt.

⁵⁶. The value for RGPu is for freshly irradiated plutonium. See Chapter 6 for a more detailed discussion on the variations in spontaneous fission background with the age of the plutonium.

that the higher the compression velocity that can be achieved, the higher the resulting yield. Let us now define three levels of technological know-how that can be available to a developer of a nuclear explosive. One can take as a basic indicator of this level the compression velocity that can be obtained for the construction of a nuclear explosive of the implosion type. First, we have the terrorist group or the sub-state ethnic group, perhaps with support from a state, at level 1⁵⁷. These can possibly achieve a compression velocity of 500 m·s⁻¹. Second, at level 2, we have the level of know-how that the United States achieved during the Second World War during the Manhattan Project, with compression velocities of about 1 000 m·s⁻¹. The general technological level is higher nowadays, and one can today count most of the world's states, with perhaps a few exceptions in the developing world, in this category. Finally, we have level 3, at which the nuclear weapon states, but also many other industrialized states, are. The technological know-how in these states would allow the construction of a device with a compression velocity of over 2 000 m·s⁻¹.

A comment can also be made about the choice of the material for the reflector/tamper of a nuclear explosive constructed using RGPu. Because the even isotopes are not fissile, i.e., they are not fissionable at low neutron energies, the reflector should not in this case be a moderator, i.e., beryllium, that slows the fast fission neutrons down while reflecting them. Natural uranium would in this case prove a better choice.

Let us now look at the results arrived at in a few studies that have been carried out concerning the possibility of using RGPu for the construction of nuclear explosives and compare these with figures above. In a Swedish National Defence Research Institute report from 1974 the authors state that^{58,59}:

1. Reactor-grade plutonium (20-30% ²⁴⁰Pu) is at compression velocities of about 500 m/s only useful for devices of at the most a kiloton yield. The function will be fairly uncertain.

2. Reactor-grade plutonium can at very high compression velocities (2000 m/s) be used in 1 kton devices with good reliability and in 10 kton devices with limited reliability."

These two scenarios correspond approximately to level 1 and level 3 technology as defined above and correspond well to the earlier analysis. In the late 1970's Alexander DeVolpi, of the Argonne National Laboratory, did some work on the possibility of denaturing reactor-grade plutonium with isotopes that would make it more difficult to use it in nuclear explosives. While doing this he made some

⁵⁷. This is not the mad-man constructing his own nuclear bomb in his garage. The likelihood that such an effort would succeed, even if he had access to fissile material, is very small.

⁵⁸. Gyldeń & Holm (1974, p. 9).

⁵⁹. This is the authors translation. The translation mentioned in the reference list is as follows:

"1. Reactor plutonium (20 to 30% ²⁴⁰Pu) is, at fusion speeds of about 500 m/sec, usable only for charges of the strength of a kiloton at most. The function will be unsafe.

2. Reactor plutonium can, at very high fusion velocities (2 000 m/sec), be used in 1-kiloton explosions with good reliability and in 10-kiloton explosions with limited reliability."

estimates of what yields could be obtained using various levels of technology⁶⁰. He states that a high technology construction would attain an average yield of about 10 kt. This is in good agreement with the above discussion.

Finally we have to say a few words about some other problems that occur when constructing a nuclear device using RGPu. First, we have the problem of heating. When the plutonium in the RGPu decays heat is produced. This heat comes mainly from the isotope ^{238}Pu , which decays by an α -decay and has a relatively short half-life, i.e., it has a high specific activity. The relatively higher amount of ^{238}Pu in RGPu means that the heating problem is more difficult for RGPu than for WGPu. The specific heat production in fresh RGPu is approximately $11 \text{ W}\cdot\text{kg}^{-1}$ compared to approximately $2 \text{ W}\cdot\text{kg}^{-1}$ for WGPu. As discussed earlier, if the temperature in the plutonium core is not kept below 115°C , the plutonium would undergo a phase change with detrimental results for the mechanical stability of the core. This can be avoided by using δ -phase plutonium alloyed with gallium which is stable at room temperature. The heating of the core may still cause problems with other materials. Meyer et al. (1977) has calculated that surface temperature of RGPu with a burn-up of $30\,000 \text{ MW}_{\text{th}}\cdot\text{days}\cdot(\text{kgU})^{-1}$, assuming natural convective cooling, to be 65°C . This is a temperature that might cause a problem in the surrounding conventional explosives.

A second difficulty concerns the radiation from the plutonium. This is also higher for RGPu than for WGPu, though it is not high enough to preclude manual handling of the plutonium. The surface dose rate from X-rays, γ -rays and spontaneous fission neutrons from a 1 kg sphere of RGPu is approximately $220 \text{ mSv}\cdot\text{hr}^{-1}$ compared to approximately $35 \text{ mSv}\cdot\text{hr}^{-1}$ for WGPu. A third, similar, problem concerns the radiation levels when reprocessing the spent fuel to produce the pure plutonium. The higher the burn-up in the spent fuel, the higher are the radiation levels that need to be dealt with when reprocessing. To reprocess "fresh" civil power reactor fuel is thus more difficult than to reprocess irradiated fuel with WGPu in it. However, the radiation levels decrease with time. In addition, reprocessing of spent civil power reactor fuel is presently being carried out at several civil reprocessing facilities.

As a summary let us cite two documents that discuss the possibilities for using RGPu in nuclear explosives. Both were written in 1976 when some efforts were put into informing the civil nuclear establishment of the risks that RGPu could be used in nuclear explosives. First, the United States Energy and Research Development Administration (ERDA) presented the following view on the matter at briefings for United States and foreign nuclear specialists that were held at a meeting of the Atomic Energy Forum/American Nuclear Society in November 1976⁶¹:

"It is sometimes asserted that fabricating a weapon from the plutonium contained in spent fuel from a power reactor is difficult if not impossible for all but industrial states with sophisticated technology at their disposal. In fact, although reactor grade

⁶⁰. DeVolpi (1979) and DeVolpi (1982A).

⁶¹. Nucleonics Week (1976).

plutonium is more difficult to work with than plutonium produced specifically for nuclear weapons it can be made into a powerful nuclear explosive. The basic arguments against the usefulness of reactor grade plutonium in nuclear weapons are that it is highly radioactive, hence difficult to handle, and that it contains isotopes which spontaneously fission, releasing neutrons that would cause pre-initiation of the chain reaction before the nuclear device was assembled. The result would be little or no nuclear yield.

In answer to the first point, although plutonium of any isotopic composition is inherently difficult to handle, many nations have developed techniques and equipment to work with plutonium in the course of recycling spent reactor fuel. With only a marginal increase in difficulty, nations so inclined could adapt these same methods to handling plutonium in the fabrication of nuclear explosives. As to pre-initiation, it is more likely to occur in a device using plutonium with a large content of isotopes that spontaneously fission but a device specifically designed to use reactor grade plutonium could produce a powerful nuclear explosion. All grades of plutonium must be considered strategically important and dangerous.”

Second, as was described above, material was in the same year collected by scientists at Lawrence Livermore National Laboratory for use in the briefing of domestic and foreign specialists from the civil nuclear establishment on the risks that RGPu could be used in nuclear explosives. In one such briefing done by Robert W. Selden he states⁶²:

“Reactor-grade plutonium is an entirely credible fissile material for nuclear explosives.

The increased neutron background does provide an incentive for a nuclear explosives program to make low plutonium-240 material”.

No country has, so far, used reactor-grade plutonium for the construction of a nuclear explosive with the intent of using or threatening to use it. Nor has a terrorist group. This does not mean that this will never happen. We have shown that it is possible. Let us hope that it will not occur. One must keep in mind that a 1 kt nuclear explosion is not a negligible explosion even though one often discusses nuclear weapons as having yields of hundreds or thousands of kt. The largest “block-buster” bombs used in World War II utilized the explosive power of about 1 tonne of high explosives. These bombs got their name from their capability of reducing one city block to rubble. A one kt nuclear explosive represents the explosive power of one thousand tonnes of conventional high explosives.

We will close off this chapter by mentioning the different needs that might exist for the testing of a nuclear explosive to be certain that it would function as intended. For a pure fission device using WGPu or WGU this appears not to be necessary, if the designers are knowledgeable, and the testing of the explosive would disclose a

⁶². As quoted in Bloom (1985, p. 24).

covert military nuclear programme⁶³. However, for the construction of miniaturized nuclear explosives, fusion-boosted fission nuclear explosives, fusion nuclear explosives, or fission nuclear explosives using RGPu, testing is probably necessary if one wants to build a reliable weapon.

We will now proceed with the final chapter of the review part of the thesis, where we describe the present planning for the disposal of spent civil reactor fuel as well as for fissile material from the reductions in the nuclear arsenals.

⁶³. Apparently both Israel and Pakistan have constructed nuclear explosives without testing them. There was, however, some discussion in the late 1970's of whether Israel had, in co-operation with South Africa tested a nuclear explosive (Marshall 1979, Marshall 1980A, Marshall 1980B, Marshall 1980C, Marshall 1980D). If this was actually the case, it seems possible that this was a miniaturized and more complicated nuclear weapon, i.e., an artillery shell, that might have needed testing.

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4. THE PRESENT PLANS FOR THE DISPOSAL OF FISSILE MATERIAL IN CIVIL AND MILITARY HIGH-LEVEL NUCLEAR WASTE, INCLUDING FISSILE MATERIAL FROM NUCLEAR WEAPONS

In this chapter we shall review the present plans for disposing of civil and military high-level nuclear waste (HLW)¹. This is a very broad subject and we have to restrict our discussion.

First, in this thesis, we are actually only interested in the HLW that includes *fissile material*, and we therefore only briefly touch upon disposal plans for high-level civil and military reprocessing waste. This is not, however, a large problem as any method that can be used for the final direct disposal of spent fuel from nuclear power reactors should be possible to use for the final disposal of high-level reprocessing waste.

The exclusion of the civil and military high-level reprocessing waste means that in this thesis the concept of HLW includes

- the spent, unprocessed fuel from the global civil nuclear power programme²,
- the reprocessed and separated civil reactor-grade plutonium (RGPu),
- the spent, unprocessed fuel from the military nuclear programmes³, and
- the fissile material, weapons-grade plutonium (WGPu) and weapons-grade uranium (WGU), in the nuclear weapons that are presently being destroyed as a result of extensive reductions in the superpowers' nuclear arsenals.

This is still a very broad subject. We will restrict the discussion further by concentrating on

- disposal solutions to the main waste stream on the civil side, i.e., the direct disposal of spent nuclear fuel, and
- the main problem on the military side, i.e., the destruction and disposal of the fissile material from nuclear weapons.

At the risk of oversimplifying the problem, we state that if these problems can be satisfactorily resolved, then all other HLW can be included in such solutions⁴.

We also have to say a few words on the term "present plans". By this we mean the *present*, in the early 1990's, most commonly considered methods for disposal of these two types of HLW⁵.

¹. The terminology used when discussing nuclear waste is described briefly in Appendix 1.

². This includes spent fuel from civil nuclear reactors of various kinds that contain various qualities of reactor-grade plutonium, spent MOX-fuel, spent fuel from many different types of research reactors and spent cores from a few fast breeder reactors.

³. This includes some spent fuel from military material production reactors containing fuel-grade plutonium, spent fuel from naval propulsion reactors and spent fuel from military research reactors. In addition there is some spent fuel in a few reactors in satellites "parked" in Earth orbit that may some day have to be disposed of.

⁴. Reprocessed and separated RGPu is very similar to WGPu, spent MOX-fuel is very similar to ordinary spent nuclear power reactor fuel, etc.

⁵. Some alternative methods for the disposal of this type of HLW are discussed in Chapter 8. There is

We shall divide the exposé in this chapter into three main parts. First, we shall in general terms look at present plans for disposing of the civil HLW to get an idea of how different countries are approaching this subject. Second, we shall describe a *reference plan* for the direct disposal of spent fuel from civil nuclear power reactors. We will do this in order to have a specific HLW disposal to analyse when in Part II of the thesis we study whether the present system for managing civil HLW will also solve the long-term nuclear explosives predicament, apart from solving the long-term environmental problems. As our reference plan we have chosen the Swedish KBS-3 method for constructing a final repository for spent fuel, the interim facilities needed until the final repository is to be filled, and in this we include the Swedish administrative system for overseeing the handling of spent nuclear fuel and the financing of the final disposal. In fact, what we shall do is to describe the Swedish system and then later in the thesis compare alternative methods of managing nuclear HLW with relevant components of the system. Third, we shall discuss the most common ideas that have been proposed for how to dispose of the fissile material from superfluous nuclear warheads. In this chapter we will concentrate on those proposals that involve using the material in the civil nuclear fuel cycle.

In addition, towards the end of this section we will look into the problems of handling other military HLW, even though this is not central to the discussion of the fissile material in HLW.

4.1 Present Plans for the Disposal of Civil High-level Nuclear Waste

Civil high-level nuclear waste (HLW) is normally defined as spent fuel from the civil nuclear power reactors that is to be directly disposed of in repositories, and the wastes produced when reprocessing such spent fuel. Traditionally, when the recycling of the plutonium in fast breeder reactors was a generally expected solution for long-term global energy supply, all the spent fuel from the civil nuclear power plants was to be reprocessed⁶. In this process, the plutonium and uranium is removed from the spent fuel and the remaining actinides and fission-products form high-level reprocessing waste. Since the middle of the 1970's an increasing number of countries have decided to forego the recycling of plutonium and instead directly dispose of the spent nuclear fuel. This method is often called the "once-through fuel cycle", a contradiction in terms. The important difference is that this type of disposal leaves the plutonium and uranium in the HLW.

The HLW is highly radioactive and will remain a health hazard for a very long time in the future. Figure 4.1 shows how the activity of the spent nuclear fuel decreases with time. We can see that it is not until after approximately 1 million years that the activity of the spent fuel has reached levels that are comparable to that

also examined whether such methods could be a way out of the long-term nuclear explosives predicament of the HLW (which is described in Chapter 6), that is not necessarily solved by the present disposal plans (as is discussed in Chapter 7).

⁶. Within large parts of the civil nuclear establishment, plutonium recycling in breeder reactors is still considered a plausible long-term energy source.

of the uranium ore that was originally mined, and even longer in time until it reaches the average activity of a typical composition of the Earth's outer crust. Because of this hazardous radioactivity, the waste has to be safely disposed of in such a way that it will remain isolated from the biosphere for up to 1 million years into the future.

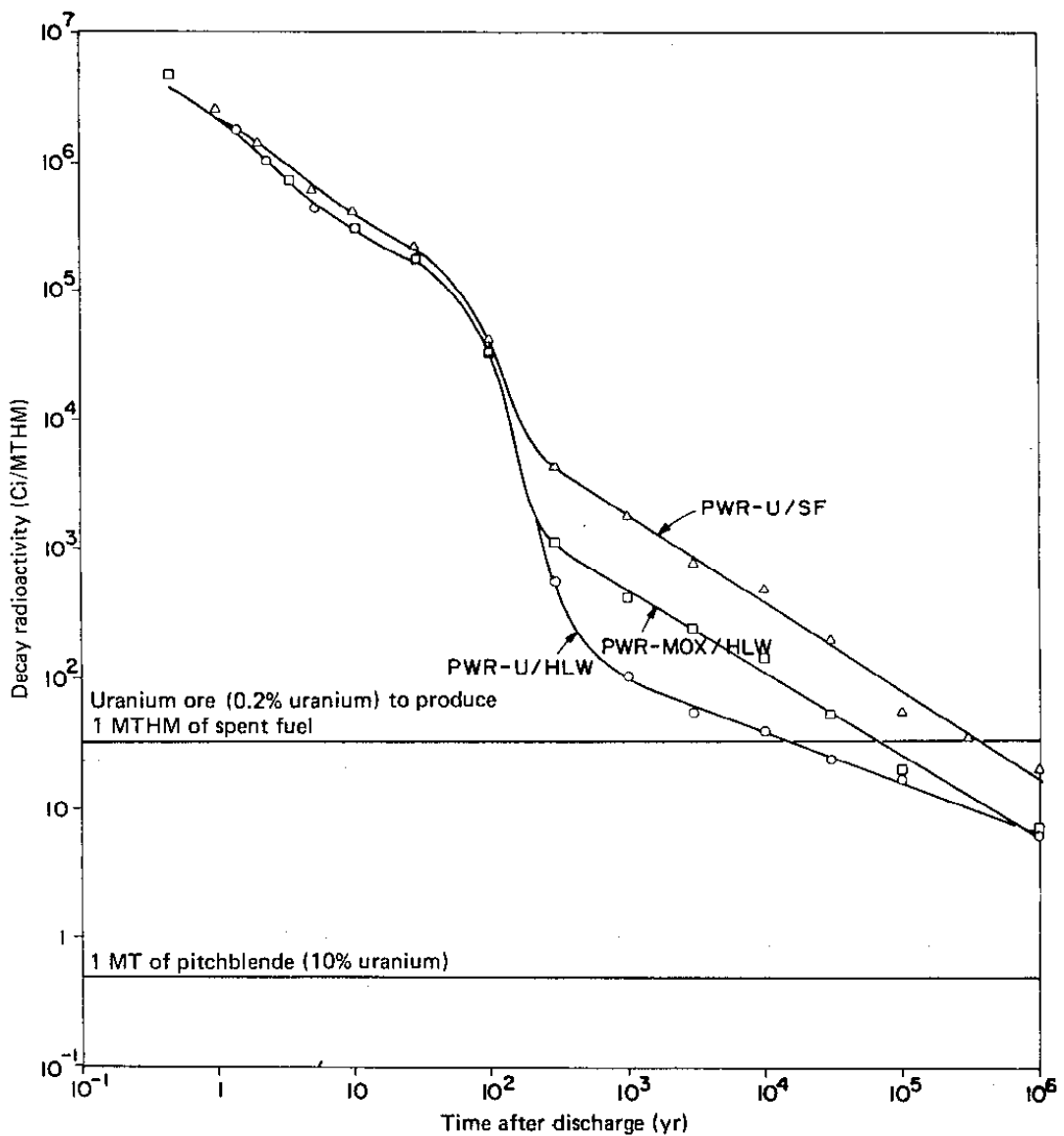


Figure 4.1. Long-term activity in spent nuclear fuel (adapted from Malbrain, Lester & Deutch (1982))⁷

⁷ The figure shows the decay activity of 1 tonne of HLW from a 1 250 MW_e nuclear reactor with a thermal efficiency of 0.33 and a burn-up of 33 000 MW_{th}·days·(kgU)⁻¹. U/SF represents ordinary spent uranium fuel, U/HLW represents the high-level reprocessing waste that would be produced if 1 tonne of such fuel were reprocessed. MOX/HLW represents a similar amount of reprocessing waste, but with MOX-fuel used as a fuel instead of LEU. The horizontal lines represents the activity of the

Many different ways of disposing of the HLW have been discussed. Presently, however, all the HLW disposal programmes that are under serious consideration in the world involve what is normally called geologic disposal⁸. This means that the HLW is put into final disposal underground in a repository in the bedrock, at depths of at least 300 m⁹. These depths are comparable to those that are encountered in normal mining operations where shafts and tunnels are excavated. There is therefore abounding experience of how to do the excavating.

There are in the world 26 countries that are operating or have been operating civil nuclear power reactors¹⁰. These countries will eventually all have to decide how the HLW from the reactors should be disposed of¹¹. Table 4.1 shows a summary of how these countries presently are planning to handle the high-level waste from their nuclear power programmes¹².

If one studies table 4.1, several interesting features can be observed. One is that many countries are still, officially, planning to reprocess their spent nuclear fuel. Whether these plans will finally be carried out can, in many, if not most, cases be strongly questioned. Many countries have already abandoned reprocessing to avoid proliferation risks and for economic reasons. Others will certainly do so. The economics of reprocessing and recycling is very questionable and many countries only keep such plans because they either have made large domestic investments in such technology or committed themselves through foreign reprocessing contracts. The plans for reprocessing can thus be difficult to abandon without loss of prestige or economic loss. Some of the countries have chosen to develop reprocessing technology in order to be able to master the technology and then have the option to

uranium ore (0.2% uranium, i.e., 500 tonnes of ore) needed to produce one tonne of uranium fuel, and the activity of 1 tonne of pitchblende with 10% uranium, i.e., a very high uranium concentration in an ore, which might usually be less than 1%. (cont.)

In the literature many similar figures can be found. Depending on what material is considered as HLW the levels of radioactivity and the times needed for decay vary. Many figures show activity and decay times of reprocessing HLW without stating specifically that it is not spent fuel, which can be misleading. See, for example Zhu & Chan (1989, p. 11).

⁸. Some alternatives that are close to being seriously considered will be described in Chapter 8.

⁹. Many bedrock materials are under consideration, from crystalline rock (granite) or sedimentary rock (shale/schist), to clay, rock salt and tuff. See, for example, Bechtold et al (1987), IAEA (1989A, p. C39), IAEA (1990A, p. C48) and Zhu & Chan (1989, p. 9).

¹⁰. In addition, China is preparing to start operation of its first nuclear power reactor. China has, however, already produced high-level nuclear waste in its military nuclear reactors. Another country that has a planned date for connecting its first nuclear power reactor to the grid is Romania. All in all, therefore, it is possible that the total number of countries that will have produced high-level nuclear waste in civil nuclear power production reactors may reach 28, or more.

Several other countries are operating nuclear research reactors. However, many of these reactors run on fuel that is to be returned to the supplying country when it has been used. Others, i.e., Israel, will have to be added to the above list, as it is producing nuclear HLW, albeit in a research reactor.

¹¹. Bulgaria, Czechoslovakia, Hungary and Romania will return the spent fuel to the foreign supplier. Finland will return parts of its spent fuel to the former Soviet Union. In the case of Bulgaria, Czechoslovakia and Hungary the supplier is also the former Soviet Union. In the case of Romania, the supplier is Canada.

¹². Table 4.1 is based on information from CEC/OECD/NEA (1984), Girardi (1986), OECD/NEA (1986), Bechtold et al (1987), KASAM (1987), Kühn (1987), IAEA (1989A), KASAM (1989), Schapira (1989), Zhu & Chan (1989), IAEA (1990A), Zorpette & Stix (1990), Cross (1991) and IAEA (1991B).

develop a military nuclear programme based on plutonium production in reactors. With the international development of a motion away from nuclear weapons, these countries now have an easier decision to take if they choose to abandon reprocessing.

Country	Reprocessing	Disposal
Argentina	Domestic	Domestic
Belgium	Undetermined/ Foreign	Domestic
Brazil	–	–
Bulgaria	Foreign	Foreign
Canada	No	Domestic
China	Domestic	Domestic
Czechoslovakia	Foreign	Foreign
Finland	No	Domestic
France	Domestic	Domestic
Germany*	Undetermined/ Foreign	Domestic
Hungary	Foreign	Foreign
India	Domestic	Domestic
Italy	Foreign	Domestic
Japan	Domestic	Domestic
Korea (South)	No	Domestic
Mexico	–	–
Netherlands	Undetermined/ Foreign	Domestic
Pakistan	–	–
Romania	No	Foreign
South Africa	–	–
Soviet Union (former)	Domestic	Domestic
Spain	No	Domestic
Sweden	No	Domestic
Switzerland	Foreign	Domestic
Taiwan	–	–
United Kingdom	Domestic	Domestic
United States	No	Domestic
Yugoslavia (former)	–	–

*Some spent fuel from the former German Democratic Republic may be returned to the former Soviet Union where it may be reprocessed.

Table 4.1. Waste disposal plans for countries that have produced high-level nuclear waste in civil nuclear power programmes

If one looks at the global plans for expanding reprocessing capacity in the 1990's and onwards, there are expansion plans that are surprisingly extensive,

considering the poor economics of recycling¹³. From a level of about 10 tonnes of separated RGPu per year at present, the reprocessing capacity is to produce 20 tonnes per year by 1995 and nearly 30 tonnes per year by the year (Albright & Feiveson 1992). There will be intense pressure from the nuclear industry on political leaders to make sure that this RGPu can be recycled, i.e., that in principle poor investments will have to be made in new MOX-fuel fabrication facilities or in a continued FBR research programme. There are very strong institutional bindings for continued reprocessing and recycling in the countries that were early to opt for this energy future. But, it is also possible that, due to mainly economic reasons, we will see the final collapse of the dream of the plutonium economy already during the 1990's.

4.2 A Reference Plan for the Disposal of Civil Spent Nuclear Fuel – The Swedish System

We will now describe a reference plan for the direct disposal of civil spent nuclear fuel. This is the Swedish KBS-3 method for constructing a final repository for spent fuel, the interim facilities needed until the final repository is to be filled, and the Swedish administrative system for overseeing the handling of spent nuclear fuel, including the financing of the final disposal. In order to put the reference plan in its historical context, we will first give a brief historical résumé of Swedish nuclear power and the development of plans for nuclear HLW disposal in Sweden.

However, let us first summarize the present level of nuclear electricity generating capacity in Sweden¹⁴. The construction of the first Swedish nuclear power reactor for electricity generation was commenced in 1966 and the first nuclear power reactors were connected to the electricity grid in 1972¹⁵. By 1985, 12 nuclear power reactors were connected to the grid. They are presented in table 4.2.

Figure 4.2 shows a map of Sweden, marked with the nuclear facilities mentioned in this section. The total net electricity generating capacity of the four Swedish nuclear power stations is presently 9 980 MW_e¹⁶. In 1990 nuclear power generated a net production of 65.3 TWh of electricity, representing 46% of the electricity produced in Sweden. The total energy use in Sweden in 1990 was 435 TWh¹⁷.

¹³. The efforts are strongest in France, the United Kingdom, West Germany and Japan, but India, Pakistan, Brazil and Argentina also have small reprocessing efforts.

¹⁴. This paragraph is mainly based on material from IAEA (1991A), SKB (1991B), NUTEK (1991A) and NUTEK (1991B).

¹⁵. A small reactor had earlier been built in Ågesta, outside Stockholm. The reactor was mainly used for district heating but also generated 10 MW_e of electricity. See also the next section.

¹⁶. The original net capacity of the 12 nuclear power reactors was to be 9 450 MW_e (SKBF/KBS 1983). The upgrading of the reactors has added over 500 MW_e to the nuclear electricity generating capacity, an amount equal to the capacity of one of the smaller Swedish nuclear power reactors. This capacity is sometimes called "the thirteenth Swedish nuclear power reactor".

¹⁷. In Swedish energy statistics, electricity generated by hydroelectric or nuclear power is counted as electricity when adding together the total energy use. Electricity generated by fossil fuel or biomass fuel, on the other hand, is added as the value of the fossil fuel or biomass fuel energy content.

We will now describe the historical development of nuclear power and nuclear waste handling policy in Sweden. After this the reference plan for final direct disposal of spent nuclear fuel will be reviewed.

Nuclear power station	Reactor	Reactor type*	Year of first commercial operation	Net electricity generating capacity (MW _e)
Barsebäck	Barsebäck 1	BWR	1975	600
	Barsebäck 2	BWR	1977	600
Forsmark	Forsmark 1	BWR	1980	970
	Forsmark 2	BWR	1981	970
	Forsmark 3	BWR	1985	1150
Oskarshamn	Oskarshamn 1	BWR	1972	440
	Oskarshamn 2	BWR	1974	600
	Oskarshamn 3	BWR	1985	1160
Ringhals	Ringhals 1	BWR	1976	800
	Ringhals 2	PWR	1975	850
	Ringhals 3	PWR	1981	920
	Ringhals 4	PWR	1983	920

*BWR = Boiling Water Reactor, PWR = Pressurized Water Reactor

Table 4.2. Nuclear power reactors in Sweden

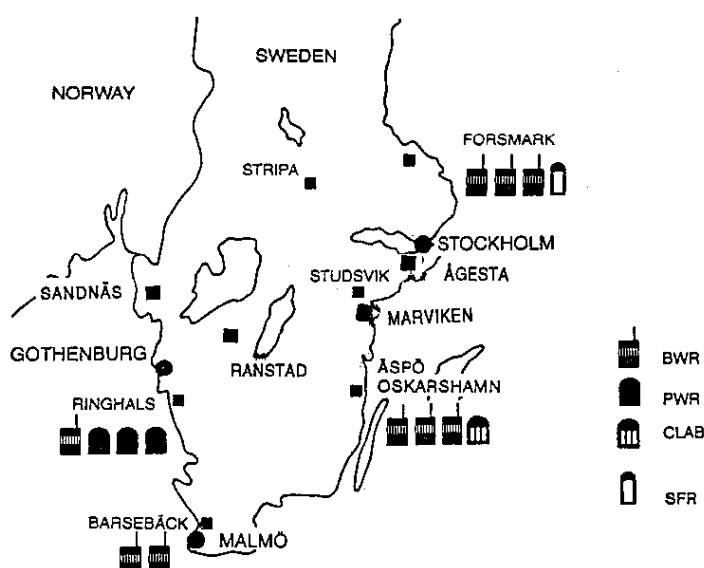


Figure 4.2. Swedish nuclear installations (adapted from SKB 1991A, p.13)¹⁸

¹⁸. Some of the sites on the map are mainly of historical interest, and may not even have been

4.2.1 *Nuclear Power and the Nuclear Waste Debate in Sweden – A Brief Historical Review*¹⁹

The Swedish nuclear programme, both military and civilian, was initiated as soon as the development and use of the atomic bomb became known in 1945. A military nuclear weapons project was started under the auspices of the Swedish National Defence Research Institute that was formed during the war. The Swedish Atomic Energy Company [AB Atomenergi] was established in 1947 with a mandate to promote civilian development of nuclear energy. At the end of 1949 the military and the civilian efforts were closely co-ordinated in a common plan to avoid duplication.

As a result of this plan the nuclear energy programme was developed to maximize the military potential of the programme. In addition, the principle was adopted that the civil nuclear programme was to be developed so as to be entirely independent of foreign technology and raw materials. Uranium was to be mined at Ranstad, near Skövde²⁰. The power reactors were to be heavy-water moderated reactors fuelled with natural uranium, a type that was easy to construct so that the fuel could be changed while the reactor was operating, an essential factor for the production of weapons-grade plutonium in low burn-up fuel. A reprocessing plant was to be constructed in Sannäs on the west coast, with critical parts excavated into the bedrock. The reprocessing plant would be needed for production of pure plutonium. The first Swedish nuclear power reactor, completed 1958 in Ågesta, a suburb of Stockholm, was placed deep down in a bunker. The reactor, called R3, with an initial output of 65 MW_{th}, generated district heat and electricity (net 10 MW_e)²¹. At this time design work was under the way for a 206 MW_{th} reactor (R4), fuelled with slightly enriched or natural uranium and moderated with heavy water, to be built at Marviken on the east coast.

The military had counted on the R3 reactor to produce 20-25 kg of weapons-grade plutonium per year and the R4 reactor to produce 40-80 kg²². The production of weapons-grade plutonium was, however, never commenced. By 1960, the military programme was in deep difficulties. There had been a change in military and political thinking on the usefulness of a Swedish nuclear weapon, strongly influenced by a growing opposition in public opinion. It was becoming increasingly difficult, for economic reasons, to motivate many parts of the programme from the standpoint of a purely civilian nuclear programme. In addition, the United States

constructed, but are mentioned in the historical résumé below.

¹⁹. This section is mainly based on Lundbergh (1959), Malmlöw (1963), Prawitz (1968), Agrell (1985), Larsson (1986), Johansson (1986), Forssberg (1987), Reiss (1988), Åhäll et al. (1988), Jasper (1990), Berkhout (1991) and Wallin (1991).

²⁰. The sites mentioned in this section are marked on the map in figure 4.2.

²¹. The power output was increased to 80 MW_{th} in 1980. The reactor was shut down in 1974.

²². These amounts of weapons-grade quality plutonium would be produced only if the reactors were operated in a way that was optimized for weapons-material production. Under the normal operating conditions, optimized for heat and electricity production, the plutonium produced in Ågesta was not of weapons-grade quality. However, as we have seen in Chapter 3, such plutonium, although in those times not considered suitable for use in weapons, can be used for the construction of nuclear explosives. The plutonium in the spent fuel from Ågesta was, in fact, more suitable for such purposes than the plutonium later produced in the Swedish light-water reactors.

showed a great concern about the Swedish military nuclear programme. In an effort to influence the direction of the Swedish nuclear development, offers were made for economical light-water reactor technology, more difficult to use for the production of weapons-grade plutonium, combined with favourable long-term contracts on United States-controlled low-enriched uranium. The Swedish nuclear power industry showed great interest in this possibility. At the same time there were construction and reactor safety difficulties with the Marviken reactor. The reactor was completed and trial runs of some systems were carried out. The core was, however never loaded and the reactor was cancelled in 1970²³. The first Swedish light-water reactor, Oskarshamn 1, was ordered in 1965 and completed in 1972. By this time the question of whether Sweden was to acquire nuclear weapons had been definitely decided. Public opinion polls showed popular support for nuclear weapons in 1957 but clear opposition from 1959 on. Diminishing military interest in nuclear weapons also reduced the pressure. In 1966 it became clear that the issue was politically dead, and this was confirmed by the unanimous parliamentary decision in 1968 not to acquire nuclear weapons. Sweden signed the Non-Proliferation Treaty (NPT) that year and ratified it in 1970.

From the middle of the 1960's until the beginning of the 1970's the role of nuclear power for electricity generation in Sweden grew and expansion plans were relatively unchallenged. A domestic nuclear industry was built up for the construction of boiling light-water reactors, fuelled with low-enriched uranium, and the nuclear future looked bright. The trade association of Sweden's electricity producers recommended that 18 reactors be brought on line by 1985 and 24 by 1990 to meet a growing electricity demand.

The abandoning of the wholly national Swedish nuclear programme, with the adoption of the light-water reactor concept in the 1970's and the import of low-enriched uranium fuel, also opened the possibility for foreign reprocessing and contracts were signed with Cogéma in France and BNFL in Britain. The plutonium was to be returned to Sweden for use in the nuclear reactors as MOX-fuel while waiting for the introduction of the fast breeder reactor (Forsström 1982A, Forsström 1982B). The reprocessed high-level nuclear waste was to be returned to Sweden.

From the beginning of the 1970's opposition to nuclear power began to develop more strongly. The environmental movement in Sweden had started to grow in the 1960's and gained strength in 1972 when the UN Conference on the Human Environment was held in Stockholm.

When the oil crisis came in October 1973, energy policy moved up to the forefront on the political agenda. By this time, eight nuclear reactors had been licensed and the main result of the oil crisis was that energy saving was emphasized as a way of reducing the dependence on foreign oil.

As it should in a democratic society, the opposition to nuclear power also spread into the political arena. By the time of the election in 1976, the Centre Party had made opposition to nuclear power a main issue in party politics. The opposition

²³. Marviken was later converted to an oil fuelled electricity generating plant, possibly the only nuclear power reactor in the world fuelled with oil.

parties won the elections and the Social Democrats lost power for the first time since 1932. Of the three opposition parties, the Centre Party, the Liberals and the Conservatives, the Centre Party was the largest and its leader, Torbjörn Fälldin, formed a government. The other two parties in the Government were pro-nuclear, the conservatives strongly so.

In the hope to be able to halt the development of nuclear power, the Centre Party in 1977 suggested a new law requiring the utilities to present detailed plans for the handling of nuclear waste as a necessary condition for taking new nuclear reactors into operation. This law, the "Stipulation Act" was presented to the Parliament by the Fälldin Government and passed by the Parliament in April 1977. This law stated that:

”Operation permission is to be granted only if the reactor owner:
– has established a contract for reprocessing of spent nuclear fuel, and further, has shown how and where a completely safe final storage facility can be constructed for the highly radioactive waste, or
– has proven how a completely safe final storage facility for spent, un-reprocessed nuclear fuel will be constructed and where it will be located.”

The response by the nuclear industry was to put much effort into the KBS project that had just started²⁴. The aim of this project was to show that bedrock disposal of highly radioactive waste from reprocessed nuclear fuel would be feasible. A large number of reports were ordered on the state of knowledge in fields related to the plans for this kind of disposal: the density of cracks in the bedrock, movement of water in such cracks, ion exchange between water and rock, properties of bentonite, properties of possible materials for encapsulation, effects of heat from the waste, etc.

The first plan, KBS-1, was presented already in November 1977 by the power industry in support of their application for starting the reactors Ringhals 3 and Forsmark 1, the seventh and eighth Swedish nuclear power reactors²⁵.

According to KBS-1, the high-level waste from reprocessing should, after 40 years of preliminary storage (for radioactive fission elements to decay), be vitrified and put into lead and titanium canisters to be buried in bentonite clay at a depth of 500 metres in bedrock of sufficient quality.

The plutonium separated in reprocessing was a potential fuel that could be returned to the power industry for use as MOX-fuel or to be sold to the reprocessing country, eventually to be used in fast breeder reactors. Since a contract on reprocessing had been signed with the French company Cogéma, France was the country that would handle Swedish-produced plutonium. This caused some criticism. France had not signed the Partial Test-ban Treaty, nor the Non-Proliferation Treaty, and it did not put a strict boundary between its civil and its military nuclear activities.

²⁴. KBS is short for Kärnbränslesäkerhet [Nuclear Fuel Safety] which was the name given to the company formed by the utilities to find disposal solutions that would meet the requirements of the Stipulation Act. This company later became SKBF and is now called SKB (see below).

²⁵. KBS (1977).

KBS-1 was reviewed by different organizational and expert bodies. A large part of them were critical, and almost every detail of KBS-1 was criticized. In the Government, the issue of KBS-1 led to a crack between the Centre Party and the pro-nuclear parties, the Conservative Party and the Liberal Party, at the end of September 1978. The Fälldin Government had to resign and a Liberal minority government took over.

The pro-nuclear parties within the previous Fälldin Government had made the Government accept KBS-1 as fulfilling the Stipulation Act apart from one condition. It was still not considered proven that a site with sufficiently good bedrock existed. The Liberal Government handed over to the Swedish Nuclear Power Inspectorate (SKI) the judgement whether sufficiently safe rock existed. New boreholes were drilled, boreholes that by many were regarded as "political". SKI, without geological expertise within itself, appointed a group of eight geologists to draw conclusions from the drilling tests. There was disagreement among the experts whether or not the rock could be regarded reliable, but on the basis of this the SKI board concluded, by majority vote, that satisfactory rock had been found. The formal approval of KBS-1 was given by the Liberal Government in June 1979, and the new reactors could be started.

Meanwhile, the KBS project continued, and a study was made of how to dispose of spent fuel directly without reprocessing. In KBS-2, completed in September 1978, detailed plans were presented for how this could be done²⁶. The main difference from KBS-1 was that one now had to deal with solid waste, and no vitrification was needed. On the other hand, the total long-term radiation release would be larger as the plutonium and uranium were not removed from the waste. The model in KBS-2 was to put the spent fuel rods into copper canisters after allowing the short-lived isotopes to decay in the intermediate storage for 40 years, and then to deposit them in a bedrock repository.

The Liberal Party, at this time in history, had much in common with the Social Democrats, also on the issue of nuclear power, and in March 1979 the Liberal Government presented an energy bill proposing that nuclear construction be stopped after 12 reactors. This was a compromise between the 13 reactors favoured by the Social Democrats and the 11 favoured by the Liberals. The bill was scheduled to be considered in June, but by this time the ground for the bill had been drastically changed.

The opposition to nuclear power outside the political scene had been growing continuously. Towards the end of 1978, the *Folkkampanjen mot Kärnkraft* [the People's Campaign Against Nuclear Power] had been formed, uniting the forces of the environmental movement against nuclear power. It called for a referendum on nuclear power, possibly in connection with the elections in September 1979. This call was supported by the Centre Party and the Communist Party in Parliament.

The Three Mile Island accident occurred on March 28, 1979. On April 4 the Social Democrat leader, Olof Palme, announced that his party now favoured a referendum and the other parties followed.

²⁶. KBS (1978). KBS-1 and KBS-2 are also summarized in English in KBS (1979).

After the election in September 1979, the second Fälldin three-party government took office. By this time there already existed an agreement among the five party leaders to hold the 1980 referendum. The government only had to administer the agreement and put it before the Parliament.

The referendum took place in March 1980. At that time, 6 nuclear power reactors were on line, 4 were ready for service and 2 were under construction. There were three "lines" to vote for²⁷. The Conservatives supported Line 1, the Social Democrats and the Liberals Line 2, and the Centre Party and the Communists Line 3. All three alternatives were for phasing out nuclear power. Lines 1 and 2 were in favour of putting at most 12 reactors on line and then to phase them out "at a rate consistent with the need for electricity to maintain employment and welfare". Line 3 said no to expansion of nuclear power and wanted to phase out the 6 currently operating reactors within at most 10 years. Line 2 differed from Line 1 in additional general statements on energy policy on the back of the ballot. This included a phrase calling for public ownership of nuclear power, since the Social Democrats did not want to appear as supporters of the same alternative as the Conservatives. Thus the Conservatives were forced to run their own Line.

When the alternatives for the referendum had been formed, it was tacitly understood, within the Government, that if the Lines 1 and 2 won a majority of votes, the Centre Party would accept the appraisal of the previous Liberal Government that sufficiently safe bedrock was available to satisfy the condition of the Stipulation Act. The question of sufficiently safe bedrock had thus been changed into a political rather than a factual issue. Just as the Liberals had handed over the responsibility to SKI, the Centre Party now handed it over to the people.

In the referendum, Line 2 got 39.1%, Line 3 38.7% and Line 1 18.9% of the votes. It was possible to interpret this result in many different ways. The main result, however, was that intended by the political parties when they agreed on the referendum, namely that the dilemma of the role of nuclear power in Sweden had been defused and could be removed from the political agenda. The Stipulation Act, introduced by the Centre Party to stop nuclear power, had thus been turned into a vehicle that took nuclear power through the decision process. Through the way the law had been used, it had lost all respect. After the Social Democrats had returned to power in 1982, they made a proposition to remove the Stipulation Act, and this was accepted by the Parliament. Instead, the Act on Nuclear Activities was passed (see below).

The result of the referendum was also interpreted to mean that 12 reactors had to be completed, although the ballots of Line 1 and Line 2 said "at most 12 reactors". In addition, in June 1980, the Parliament approved briefly formulated legislation to the effect that Sweden would phase out its nuclear power by 2010, a date that the Social Democrats had used in the referendum campaign.

After the referendum, the public debate on the disposal of nuclear waste has been limited, apart from resistance from local groups at possible repository sites (see

²⁷. The word *line* is used here to represent the Swedish word *linje*, which is used both to represent a bus *route* or a railway *line* as well as an alternative or option.

note 40).

The referendum and the Parliament decision based on it to phase out nuclear power by 2010, put an upper limit to the use of nuclear power in the country. This meant that to build up a recycling capacity to save uranium fuel in the long term was less desirable. In addition, the reprocessing industry was getting a bad reputation and the economy of recycling was becoming questionable. Also, the stand of the United States, where the Carter administration was opposed to reprocessing because of the risk of the proliferation of nuclear weapons, had influenced the Swedish Government. A decision was taken to avoid reprocessing and instead opt for the direct disposal of the spent fuel²⁸.

When this decision was taken, the KBS-2 report was up-dated to a later version, KBS-3, which was presented in May 1983 (SKBF/KBS 1983). The KBS-3 method is still, at present, the reference plan for a method for final disposal of Swedish spent nuclear reactor fuel in a repository in the bedrock. It is described in the next section.

In 1982 the Social Democrats regained power and they have held the main responsibility for Swedish energy policy until the elections in September 1991. Since the 1980 referendum the Swedish electricity generation has increased from 94.0 TWh per year to 142.1 TWh in 1990 as shown in figure 4.3. The largest part of this increase is due to nuclear power.

The net electricity use per inhabitant in Sweden is among the highest in the world (see figure 4.4). In order to be able to absorb all this power in the market, electricity prices have been kept low, especially for industry. Conservation campaigns were discontinued and electric heating of private housing was encouraged. The latter was against one of the policy statements on the back of the ballot of Line 2, the line that had been supported by the Social Democrats and the Liberals²⁹.

In addition, as the nuclear power plants provide base-load electricity, some of the hydroelectric power stations that would normally also be used for base-load have been converted to be able to take care of peak power. Fossil fuel electricity generation has been minimized. Although some research effort has been put into finding alternatives to nuclear power, the low electricity prices have effectively prevented the growth of a market for solar, wind or biomass energy.

The Chernobyl accident, that affected Sweden strongly, both physically with fallout and mentally, did for a short time put nuclear power back on the political

²⁸. This decision created a problem of how to disengage from the previously contracted foreign reprocessing capacity in order to only have to plan for final disposal of one type of high-level waste, spent nuclear fuel. 140 tonnes of spent fuel is in fact to be reprocessed by BNFL in Britain, but no waste from this reprocessing will be sent back to Sweden. The reprocessing capacity at Cogéma in France was in 1989 transferred to eight German companies. The 57 tonnes of spent fuel already sent to France was traded for 24 tonnes of German spent MOX-fuel. SEK 500 million has been reserved for the costs involved in transferring the Cogéma reprocessing contracts, and future costs for reprocessing at BNFL are of the order of SEK 374 million (SKB 1991B, p. 3 and p. 23). MOX-fuel is a nuclear power reactor fuel where oxides of uranium and recycled plutonium from reprocessing are mixed. Spent MOX-fuel, while having a different composition from ordinary spent nuclear fuel, is considered similar enough to allow the use of the same nuclear waste disposal system for this spent fuel as for the ordinary spent fuel. Note: 1 USD (US dollar) \approx 6 SEK (Swedish kronor).

²⁹. Another broken "promise" from the ballot of Line 2 was that to nationalize nuclear power.

agenda. The public was, however, assured that a similar thing could not happen in the Swedish nuclear reactors, as they are among the safest in the world. A decision was, however, taken in Parliament that the phasing out of the first two reactors would begin in 1995 and 1996.

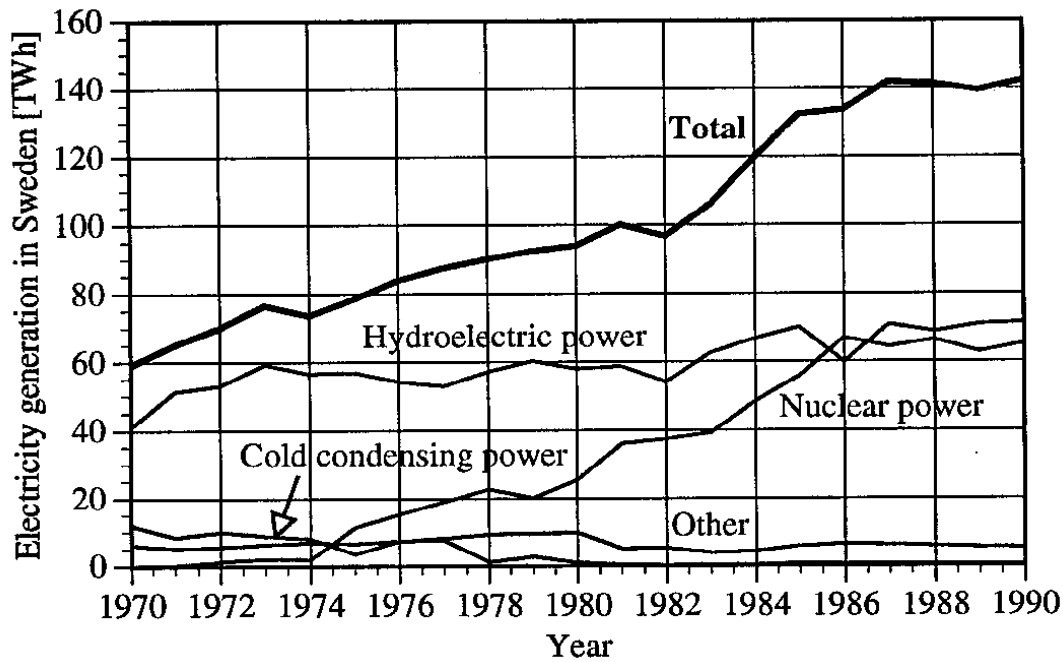


Figure 4.3. Swedish electricity generation 1970-1990³⁰

Towards the end of the 1980's, as the date for closing the first nuclear reactors in the mid 1990's was getting closer, the Social Democrat's Minister for Environment and Energy, Birgitta Dahl, started to push for a harder line to be able to enforce the closing. This led to the taking over of energy policy by the Ministry of Industry. The strength of the trade unions who strongly support nuclear power and the industrial lobby was clearly shown.

In an effort to remove the energy issue from the election campaign in the autumn of 1991, and to guarantee a continuity in energy policy, should the Social Democrats lose the elections, an "energy settlement" was concluded between the Social Democrats, the Liberals, and the Centre Party in the spring of 1991. The date for the shutting down of the first reactor was now removed. Instead, a yearly "control station" would review the progress towards the goal of shutting down all the reactors by 2010, the date still being kept. More effort would be put into making renewable energy sources economically viable energy alternatives.

The Social Democrats lost the 1991 elections and the opposition formed a four-

³⁰. Source: NUTEK 1991B, table 17. The "other" generation sources are industrial backpressure, combined heat and power and gas turbines.

party Government³¹. The Conservative Party is now the biggest party in the Government, but the Centre party, whose leader, Olof Johansson, is Minister of Environment, is still opposed to nuclear power. The Conservatives, however, hold the ministerial post in the Ministry of Industry and are therefore in charge of day-to-day energy policy. The supervision of the handling of nuclear waste is, however, under the auspices of the Department of Environment. It is, so far, difficult to see any strong tendencies towards a change in energy policy by the new Government.

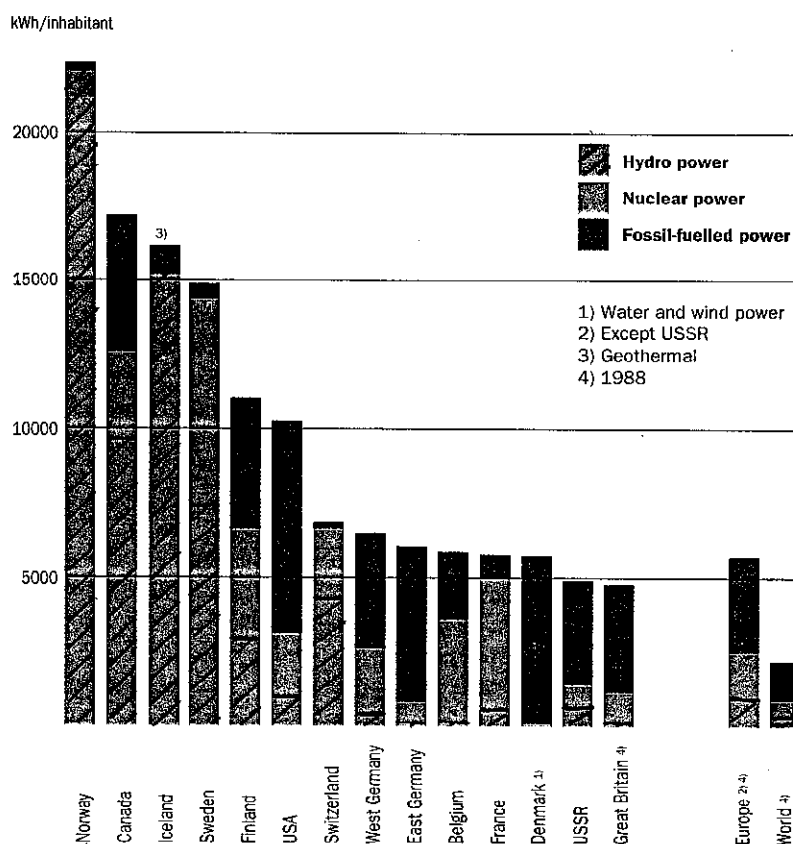


Figure 4.4. Net electricity use per inhabitant in selected countries in 1989 with relative proportions of power sources (from NUTEK 1991A, p. 18)

Sweden is strongly dependent on nuclear power for electricity generation. The fact that the referendum was set to put as many as 12 nuclear reactors on line has made the phasing out of nuclear power more difficult. The surplus of electricity has been absorbed by changing the energy infrastructure towards a dependence on cheap electricity. The nuclear industry, the utilities running the nuclear power plants, the electricity intensive industry and the trade unions intensified their information

³¹. The four parties are the Conservatives, the Liberals, the Centre Party and the Christian Democratic Party.

campaigns on the need for nuclear power in the late 1980's³². This has definitely influenced Swedish opinion and policy on nuclear power.

4.2.2 *The KBS-3 Method and the Swedish System for Managing Spent Nuclear Fuel*

Sweden is internationally considered to have one of the most advanced, if not the most advanced, systems for the management and disposal of nuclear waste. The decision to phase out nuclear power in Sweden has played an important role in the development of such a system. First, it made the reprocessing and recycling of the waste uninteresting and the decision was taken to directly dispose of the spent fuel. But, perhaps more importantly, it has set an approximate upper limit for the total amount of nuclear waste that will have to be disposed of and an approximate date for when this has to be done. This means that the planning for the final disposal of the nuclear waste is a limited problem and that a time-scale has to be developed where all the different components of waste disposal are included. This has led to the advanced Swedish system for nuclear waste disposal³³.

The KBS-3 method is still, at present, the reference plan in Sweden, for a method for final disposal of Swedish spent nuclear reactor fuel in a repository in the bedrock. In this thesis it is part of a reference plan that also includes the Swedish administrative system for overseeing the handling of spent nuclear fuel and the financing of the final disposal. Both of these are described in this section.

The KBS-3 method has as a fundamental condition that a site can be found where there is a bedrock without major formations of cracks and that it is large enough to accommodate a repository. The hydrology and the chemical characteristics of the ground water and bedrock also have to be favourable. This means that a comprehensive examination has to be made of the bedrock before a site is chosen. The depth chosen for the repository is dependent on the bedrock, but would be approximately 500 m.

To make the repository less dependent on the quality of the bedrock, the spent fuel is to be surrounded by technical barriers. The spent fuel rods are to be encapsulated in copper canisters, of which two suggested types are shown in figure 4.5³⁴.

³². The campaigns to influence decision-makers and public opinion are well described in Wikdahl (1991) and SKB (1991A). The Swedish Nuclear Fuel and Waste Management Co. (SKB) is reimbursed from the National Board for Spent Nuclear Fuel (SKN) for its information campaigns using the funds deposited for the disposal of the spent fuel. In 1990 SEK 21.4 million of this money was used for information, an increase from SEK 9.3 million in 1989 and from a level of around SEK 6 million earlier. SKN was funded by SEK 13.3 million from waste disposal fees in 1990 and SKN's information budget in 1990 was only about 5% of that of SKB. This has caused some concern within SKN (SKN 1991D, appendix 2, p. 6 and SKN 1991C). Note: 1 USD (US dollar) \approx 6 SEK (Swedish kronor).

³³. One should, however, not forget that it was the "Stipulation Act" that started the process, and that the KBS-1 method was developed for reprocessing high-level waste, i.e., at a time when the decision to forego reprocessing was not yet taken.

³⁴. The copper canisters can be of two types, either a copper canister sealed by electron-beam welding where the copper surrounds the fuel and the space in between is filled with lead, or a copper canister

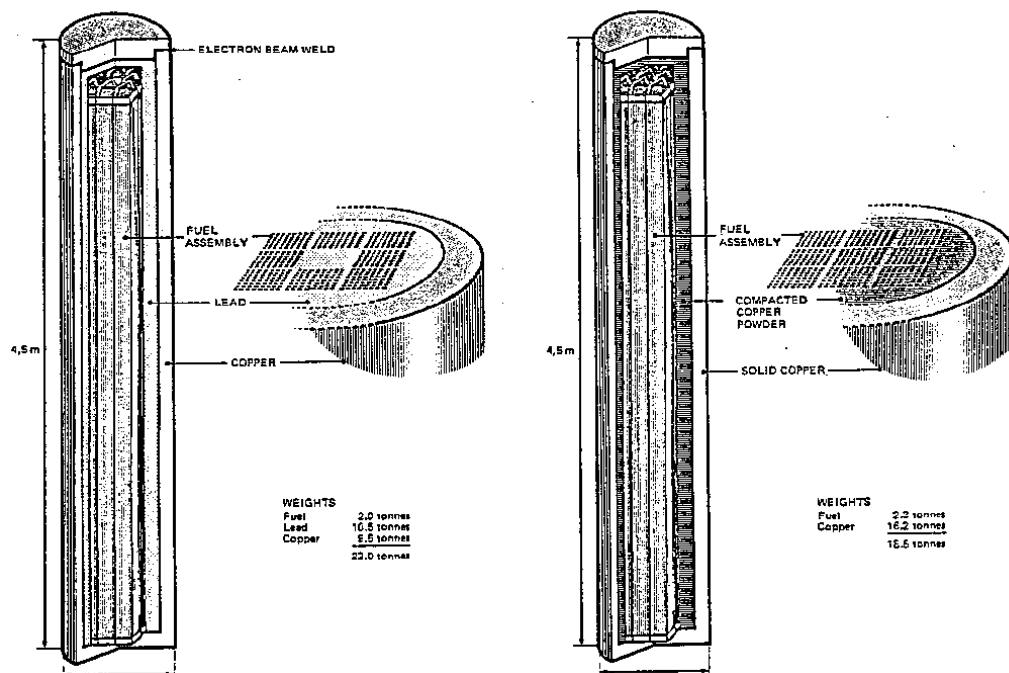


Figure 4.5. Copper canisters for encapsulation of spent nuclear fuel (from SKBF/KBS 1983, p. 10:2-10:3)

In addition, the canisters are to be surrounded by bentonite clay in the repository. The combination of copper, resistant to corrosion, and clay, resistant to diffusion, is expected to make up a man-made barrier that, together with the natural barrier of the bedrock, is to prevent the radioactive material from reaching the biosphere for a very long time-span. A canister made of copper with a wall thickness of a few centimetres is expected to remain intact and leak proof for at least 1 million years. The bentonite clay is expected to retain its buffering qualities for some million years, provided the temperature of the repository does not exceed 100°C. The repository is to be constructed to reach a maximum temperature of 80°C. The very low rate of ground water flow in the bedrock is to ensure that the leaching of radioactive substances that are left in the fuel when the canisters have been penetrated will be extremely slow.

The copper canisters are to be lowered into individual vertical boreholes in an emplacement tunnel reached through a vertical entrance shaft (see figure 4.6). The boreholes are lined with bentonite (see figure 4.7) and, after emplacement, the tunnels are filled with a sand and bentonite mixture (see figure 4.8).

sealed by means of hot isostatic pressing where the space between the fuel rods and the copper is filled with compacted copper powder. Other materials are still being investigated, one of them being a combined copper and steel shell with the copper outside. This would bring down the costs for the acquisition of copper.

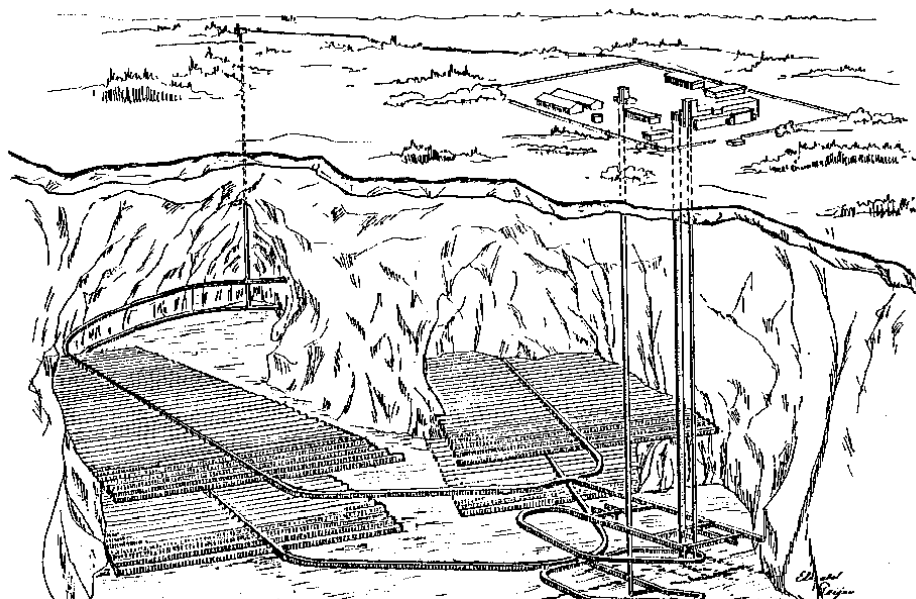


Figure 4.6. Tunnels and shafts in a final repository for spent fuel (from SKBF/KBS 1983, p. 4:17)

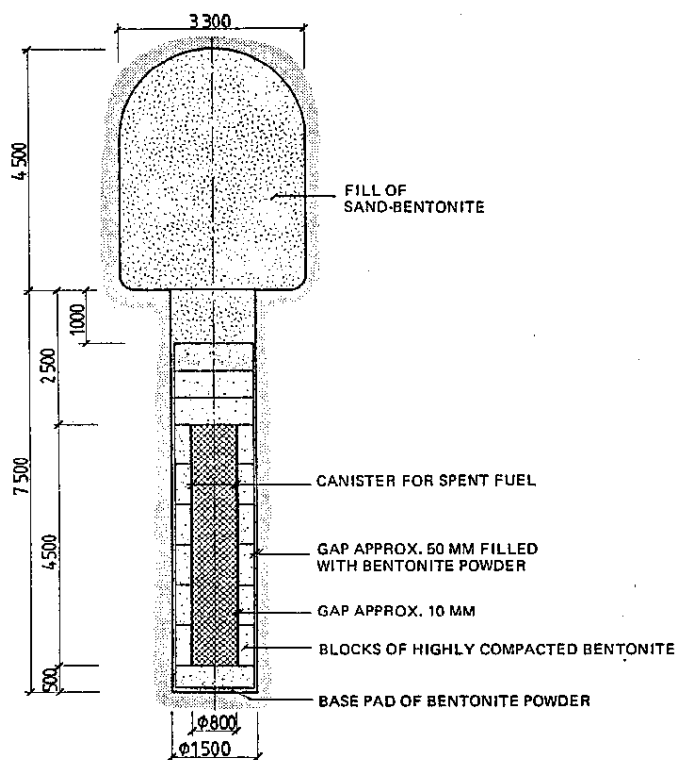


Figure 4.7. Deposition hole with canister and buffer (from SKBF/KBS 1983, p. 4:16)

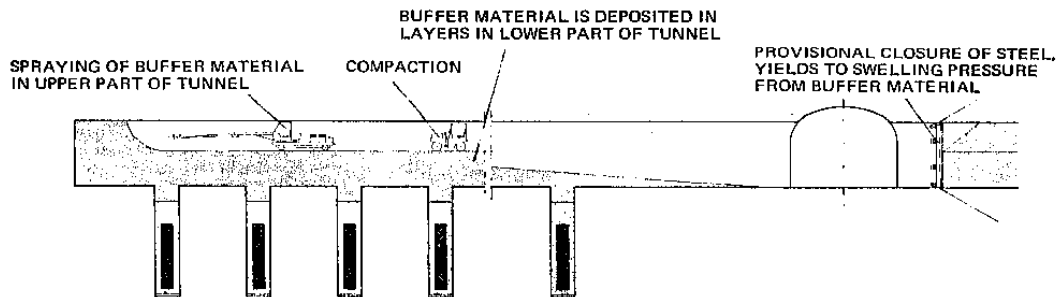


Figure 4.8. Filling of tunnels (from SKBF/KBS 1983, p. 4:16)

The total amount of Swedish spent nuclear fuel to be disposed of by the time the last nuclear power reactor is taken out of service, is approximately 7 800 tonnes. It is the intention of the Swedish Parliament and the Government that the nuclear radioactive waste produced in Sweden be disposed of in Sweden. The State has the overall responsibility for the nuclear waste. A legal and organizational framework has been set up (figure 4.9) to supervise the development of a regime for nuclear waste disposal.

The Act on Nuclear Activities of 1984 stipulates that the management and final disposal of radioactive wastes from nuclear electric power production in Sweden is the responsibility of the owners of the nuclear reactors. This means that the reactor owners have the direct responsibility for the final disposal of the nuclear waste. The act stipulates that the nuclear power reactor owners present and carry out a comprehensive research and development programme that leads to safe disposal. The four utilities that own and operate the Swedish nuclear power reactors³⁵ have formed a daughter company, the Swedish Nuclear Fuel and Waste Management Company (SKB), which they have commissioned to conduct such a programme³⁶. A report on the research and development programme is to be delivered for review every three years. The latest report was delivered in September 1989 (SKB 1989A).

The task to review the reactor owner's research and development programmes on the management and disposal of spent fuel is carried out by a Swedish Government agency, the National Board for Spent Nuclear Fuel (SKN)³⁷. The latest

³⁵. These are Vattenfall [The Swedish State Power Board], which operates the Ringhals nuclear power station, Sydsvenska värmekraft AB (Sydkraft), operating the Barsebäck nuclear power station, OKG AB, operating the Oskarshamn nuclear power station, and Forsmarks Kraftgrupp AB, operating the Forsmark nuclear power station.

³⁶. SKB has a central staff of 55 persons. In total about 500 persons are involved in SKB waste handling work (SKB 1991A, p. 13). SKB (Svensk Kärnbränslehantering AB) was formerly called SKBF (Svensk Kärnbränsleförsörjning AB) and was originally KBS (Kärnbränslesäkerhet).

³⁷. In 1990 SKN had a staff of 9 people. In order to further strengthen the agency, a scientific advisory council, the National Council for Nuclear Waste [Statens råd för kärnavfallsfrågor], has been attached to SKN since 1990. Previously this role was taken by KASAM, Samrådsnämnden för kärnavfallsfrågor [The Consultative Committee for Nuclear Waste Management]. The new council has, however, kept the old committee's acronym, i.e., KASAM.

review was carried out on the 1989 SKB report and published in March 1990 (SKN 1990B). Finally, the Government has its say and makes recommendations for the continued work.

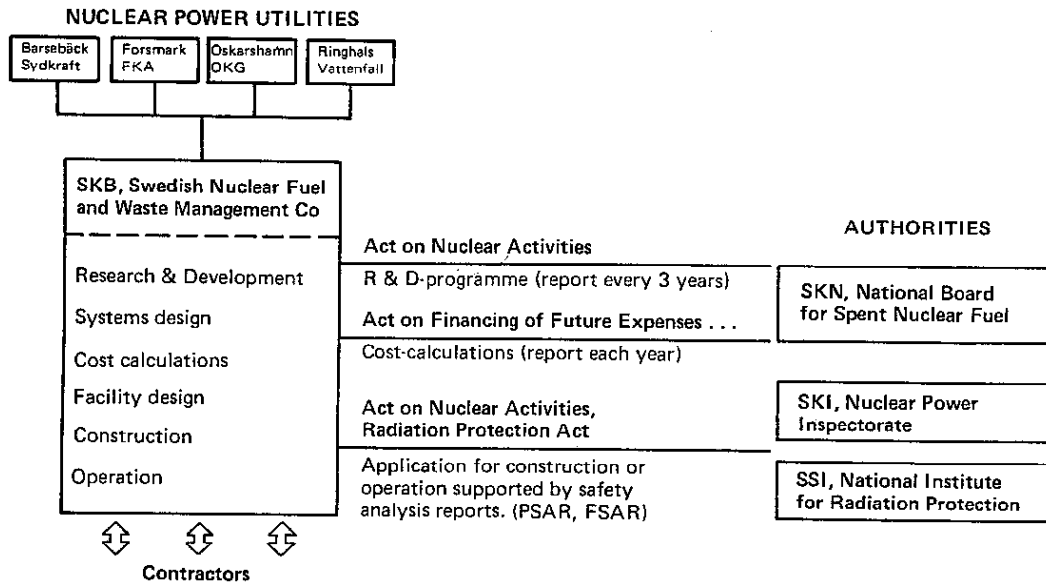


Figure 4.9. Legal and organizational framework of Swedish nuclear waste handling regime (from SKB 1991A, p.14)

At present³⁸, as previously mentioned, the main plan for final disposal of spent fuel from the Swedish nuclear power reactors is based on KBS-3. The final site for such a repository has not been chosen so far and the spent fuel is presently in intermediate storage, awaiting final disposal. SKB claims that a complete system has been planned for the management of all residues from the 12 nuclear reactors and from research facilities. The nuclear waste disposal system is planned for nuclear wastes generated until 2010, when the last nuclear power reactor is supposed to be shut down. The amounts of nuclear waste involved are shown in figure 4.10.

As shown in figure 4.11, the spent fuel, after removal from the reactor, is presently transported to a central interim storage facility for spent fuel (CLAB). The transports are made on the ship Sigyn, which is specially constructed for the handling of spent nuclear fuel and other radioactive waste.

³⁸. This description is mainly based on SKBF/KBS (1983), Forsström & Papp (1988) and SKB (1991A).

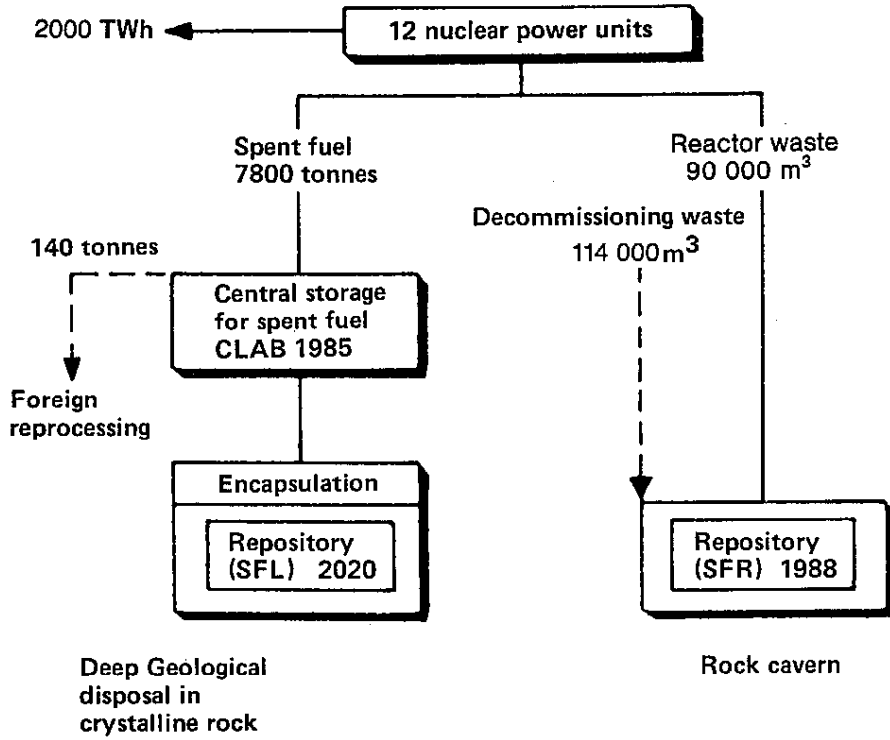


Figure 4.10. Estimated total amounts of nuclear waste to be disposed of in Sweden (from SKB 1991A, p.16)

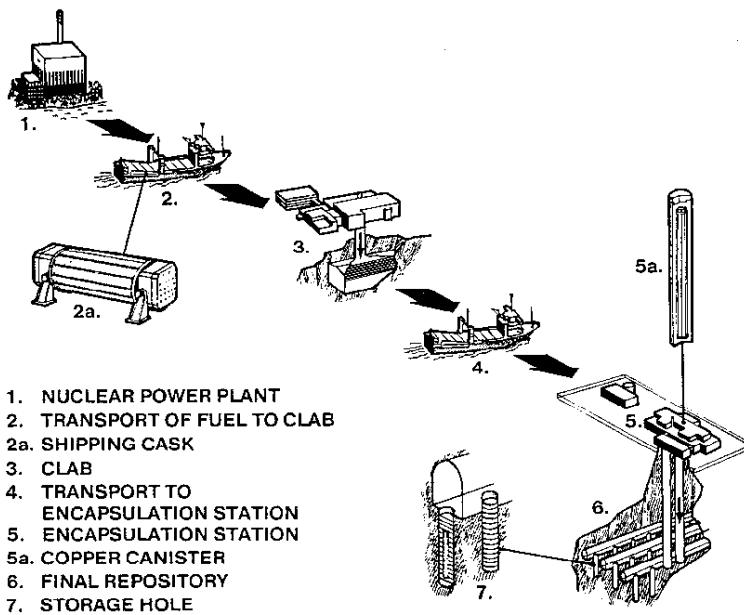


Figure 4.11. Transportation of spent fuel (from SKBF/KBS 1983, p. 3 in Summary Volume)

CLAB, which was taken into operation in 1985, is shown in figure 4.12. The facility presently has a capacity for storage of 3 000 tonnes of spent fuel. With more efficient utilization of the space available in the existing pools, its capacity will be increased to 5 000 tonnes³⁹. The total amount of spent fuel produced in the Swedish nuclear power programme is expected to be 7 800 tonnes. The total receiving capacity is 300 tonnes per year.

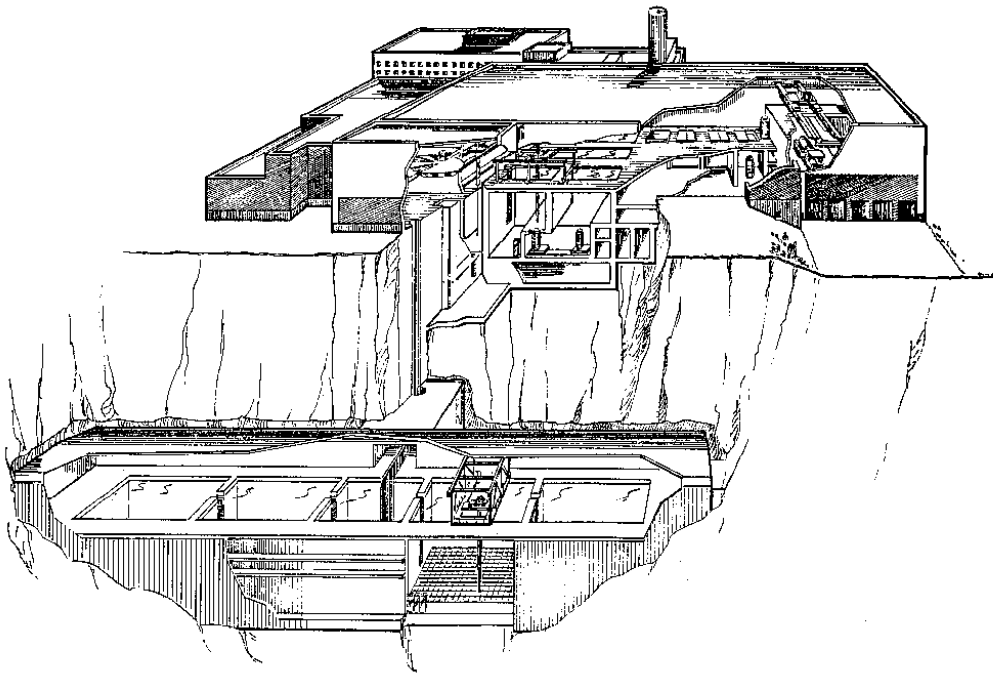


Figure 4.12. CLAB (from SKB 1989A, p. 20)

The present schedule for the final disposal of the spent fuel is shown in figure 4.13. After approximately 40 years of interim storage in CLAB, the spent fuel is to be encapsulated and deposited in the bedrock. The encapsulation and disposal facility will only start operation around 2020.

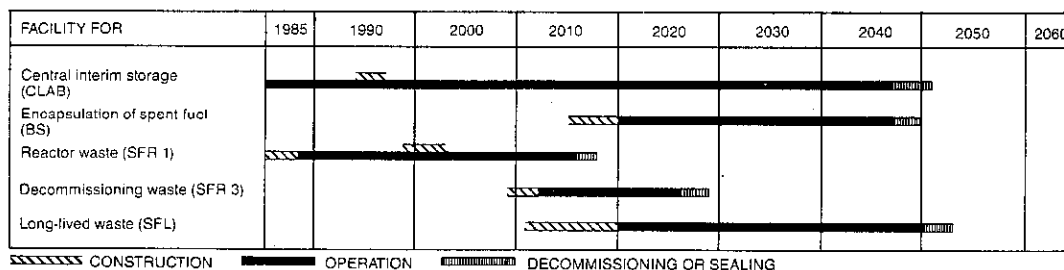


Figure 4.13. Overall timetable for facilities in the Swedish nuclear waste management system (from SKB 1989A, p. 23)

³⁹. The permission to increase the capacity of CLAB in this way has recently been granted.

The present schedule for localizing the site for a final repository for spent fuel is shown in figure 4.14. Since the beginning of the 1980's a number of sites have been discussed or examined, often leading to intense local opposition⁴⁰. During 1992 SKB will publicly announce three sites that they consider to be suitable for a final disposal repository and the site selection will continue until one site is found and construction can start in approximately the year 2010.

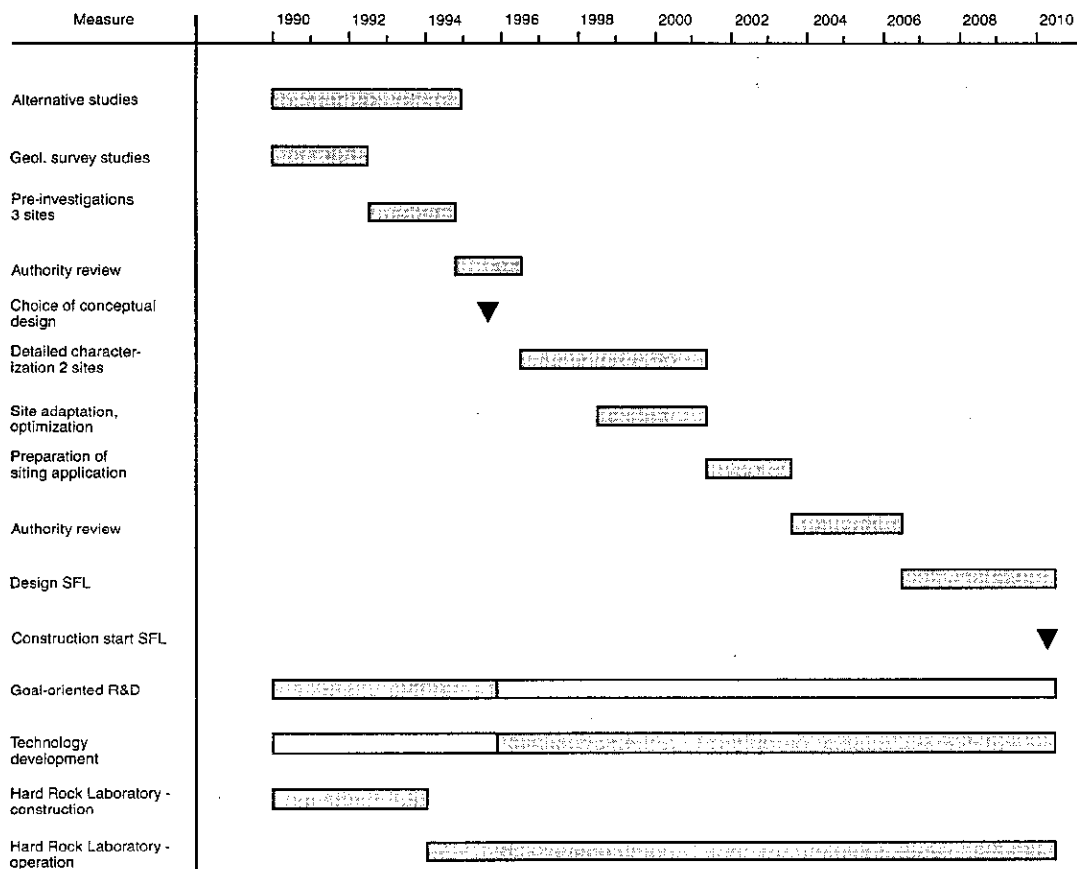


Figure 4.14. Overall timetable for design and siting of final repository for spent fuel (from SKB 1989A, p. 27)

According to the present plans, a licence application for a final repository will be prepared just after the year 2000. A licensing period of about 10 years is foreseen. The authority that will supervise the safety provisions in the licensing process is the

⁴⁰ A good example is the constant watch being kept at Kynnefjäll, where people have been, on rotation, sitting in a small cottage guarding an access road for over 11 years (see Noresson 1985). The local opposition groups are joined in a network, Avfallskedjan [the Waste Chain], pressing for responsible waste handling and energy policies.

Swedish Nuclear Power Inspectorate (SKI). To prepare the authority for this task a five-year research project called Project-90 was started in 1986. The results of the project have been summarized in a report (SKI 1991). The main emphasis of the project was to develop performance assessment resources and methodology that could be used as tools for the safety evaluation of a final repository for spent fuel.

As mentioned above, the reactor owners have to conduct a comprehensive research and development programme to find the best method for the safe disposal of nuclear waste. The latest plan was published by SKB in 1989 (SKB 1989A). The research plan is very comprehensive, involving nuclear waste safety studies, the final structure of the waste disposal system, technical barriers, bedrock qualities, chemistry, natural analogies and biosphere studies. The work is done with an extensive international co-operation. The largest present research investment is in the Aspö laboratory outside Oskarshamn, an underground bedrock laboratory⁴¹. The construction of the laboratory was started in October 1990 and it is expected that it will be ready for use, at a depth of 500 m, in mid-1994 (SKB 1991B, p. 8).

Besides reviewing SKB's research programme SKN also administers the Swedish system for financing nuclear waste management. The main principle for financing the disposal of nuclear waste in Sweden is that the costs are to be borne by those who use nuclear power. This means that a fee is paid by the utilities for every kWh of electricity generated with nuclear power. The fee is put into to a long-term fund administered by SKN and deposited in the National Bank of Sweden. According to the 1981 "Act on the financing of future costs for spent nuclear fuel, etc." the reactor owners each year have to present an estimate of the total costs for all measures that have to be taken in order to take care of spent nuclear fuel and radioactive waste from the nuclear reactors, and for decommissioning of the nuclear reactors. This calculation, called "Plan", is made by SKB and submitted to SKN. SKN reviews the plan and in its turn presents its own "Plan" to the Government where it proposes the fees on electricity to be set for the next year. The Government then decides the fee⁴².

The fees are individual for each reactor station, and therefore vary according to, for example, the age of the reactors at the station⁴³. In its fee calculations, SKN has used the 25-year economical depreciation time for the reactors that the utilities use, as the time period for which the fee shall be paid. The last reactor, Forsmark 3, was put on line in 1985. This means that the last reactor will reach an age of 25 years in the year 2010.

The total future cost (from 1992 onwards) for the disposal of the Swedish nuclear waste, including the decommissioning of the nuclear reactors is estimated to be SEK 46.0 billion in January 1991 prices⁴⁴. Until 1991 SEK 8.1 billion in current value had been spent (SKB 1991B). In 1991 the fees for the reactor owners averaged

⁴¹. The laboratory is described in SKB (1989B) and SKB (1991A, pp. 101-108).

⁴². The last two SKB "Plans" are SKB (1990A) and SKN (1991B). The last two SKN "Plans" are SKN (1990C) and SKN (1991D).

⁴³. If the reactors are older, the time that remains to collect the part of the fee related to fixed costs is shorter, and the fee therefore higher.

⁴⁴. 1 USD (US dollar) \approx 6 SEK (Swedish kronor).

SEK 0.019 (USD 0.0032) per kWh produced⁴⁵. The year before the reactor owners had paid a total of SEK 1 236 million in fees (SKN 1991D). The fee has been the same, in current SEK, since 1984, i.e., for the last 8 years. Both in 1989 and 1990 SKN proposed that the fee be raised for the following year, but the Government decided that the fee should remain the same as previously⁴⁶.

The "energy settlement" (see above) between the Social Democrats, the Liberals and the Centre Party in the spring of 1991, not setting a commencement date for the shutting down of the nuclear power plants, in principle made it possible for both SKB and SKN to reconsider the basis for earlier fee calculations. In its cost estimate to be used as a basis for the calculation of the fee for 1992, SKB assumed that all reactors will be operated until 2010 and pointed out that the reactors have been constructed for a life-span of at least 40 years. SKN, however, decided that it needs to reconsider only the calculations that involve the shutting down of reactors in 1995-96, and did no calculation for the scenario that SKB suggested. Instead it proposed that the same principle as before be kept, i.e., that the fee for 1992 is calculated using the 25 year economical depreciation time as the time during which the reactor owners shall pay the fee for a reactor. SKN added that this only means that the reactors operating after this time will have a considerably lower fee, about SEK 0.003 per kWh. It recommended that the fees for 1992 be raised by SEK 0.003 per kWh to SEK 0.022 per kWh. It now remained to be seen if the Government would follow this recommendation. In December 1991, however, the Government decided that the fees should not be raised for 1992 and would thus remain at the nominal level used since 1984 (Swedish Government 1991). This decision was motivated by a wish not to pre-empt the work of a committee that is presently reviewing the possibility of increasing the annual yield of the deposited funds. SKN has proposed that the "Act on the financing of future costs for spent nuclear fuel, etc." be modified to be able to diversify the investments of the fees paid by the reactor owners to be able to get a better yield on the funds (SKN 1991B).

This brings up the subject of an important factor that strongly affects the fee calculation, namely the long-term real interest level that is expected for the funds deposited in the National Bank of Sweden. Depending on the level used, up to as much of half of the total costs for disposal of the nuclear waste can be covered by interest on the deposited funds. The real interest is usually understood to be connected to the real growth in GNP. This means that long-term GNP growth is a

⁴⁵. The fees for the nuclear power stations were SEK 0.019 for Forsmark and Ringhals, SEK 0.017 for Oskarshamn, and SEK 0.022 for Barsebäck. In addition, since 1989 all four utilities pay a fee of SEK 0.001 per kWh for the cost of handling operating wastes. This waste handling is mainly done at Studsvik, where there is a facility for treating low- and intermediate-level waste as well as two research reactors.

⁴⁶. The main motivation for not raising the fee for 1990 was that the Cogéma reprocessing contracts had been bartered away and the costs needed to be reserved for these were lowered. (SKN 1990C). For the electricity produced in 1991 SKN wanted the fee to be on average SEK 0.022 to 0.023, depending on whether two reactors were to be decommissioned in 1995-96 or not, the higher value reflecting the increase in the fee this would give for the utilities that the decommissioning would affect. In December 1990 the Social Democrat Government decided that it did not want to pre-empt the "energy settlement" (see Section 1) with the Liberals and the Centre Party that was being prepared for 1991 and hence did not raise the fee for 1991.

necessity for the financing of the disposal of the Swedish spent nuclear fuel. The last funds will not be used until the 2050's. SKN estimates that the GNP growth in Sweden for the 1990's is to be below rather than above 2%, but sees the integration of Sweden into the European capital markets as beneficiary and assumes that the use of 2.5% real interest on the deposited funds is reasonable as a base for the 1992 fee. It does, however, state that "the Board does not see it proper to base the calculation on an average yield that lies above 2.5% under the very long time-span, about 70 years into the future, that the calculations cover".

A final comment can be made on the importance of the fee for the economy of Swedish nuclear power. It may seem as though the fee for waste handling, being relatively small compared to the final price the consumer pays, would not to a large extent influence the economy of the nuclear power reactors. However, waste handling costs together with the fuel costs of approximately SEK 0.027 per kWh (SKB 1991A) and other daily variable costs gives a marginal cost to produce electricity from nuclear power in Sweden of approximately SEK 0.06 per kWh⁴⁷. In 1990 there was a net export of 1.8 TWh of electricity from Sweden (KRAFTSAM 1991, p. 21)⁴⁸. The price paid for this electricity was about SEK 0.09 per kWh⁴⁹.

It would thus seem to be profitable, even on the margin, to run the nuclear power plants. The problem is that daily marginal cost is not the same as the marginal cost of keeping a reactors in operation, compared to permanently shutting it down if there is no need for the electricity⁵⁰. This marginal cost for electricity production is about 0.10 SEK/kWh⁵¹. One reason for not shutting down a reactor in this a case could be expected future higher export prices for electricity. It can be noted that the variable cost for hydroelectric power is neither burdened by fuel costs nor a waste handling fee⁵². The export of hydro-electricity is thus more profitable than the export of nuclear electricity.

Of interest within the Swedish nuclear waste management system is also that, with the development of a very advanced nuclear waste disposal system, a possibility seems to have opened for a very wide and free discussion of the implications of having to dispose of very long-lived nuclear waste. In Sweden, SKN has shown a

⁴⁷. The other daily marginal cost is the difference between keeping the nuclear power reactor running or shutting it down on a short-term basis. In practice, one can not shut down and restart nuclear reactors at will. The build-up of so called "pile poisons" in the core after a reactor is shut down means that one has to wait some time before a restart can be done. This makes a nuclear reactor suitable for base-load electricity production but less suitable for peak production. Lowering the power of the reactor is, however, possible. In this case, the marginal cost to produce electricity is the fuel and waste handling costs, i.e., about 0.05 SEK/kWh.

⁴⁸. Total electricity production in Sweden that year was 142.1 TWh, where 44.7% was produced by nuclear and 50.1% by hydroelectric power (NUTEK 1991B).

⁴⁹. This is intended to be the average between the 0.06 SEK/kWh marginal cost for Swedish nuclear power and 0.12 SEK/kWh marginal cost for Danish coal-based electricity production.

⁵⁰. The main additions are personnel costs and maintenance.

⁵¹. The total costs to produce nuclear electricity in Sweden in 1990 was approximately 0.189 SEK per kWh. Capital costs, which have to be paid even if a reactor is shut down permanently, represent about SEK 0.089 of these.

⁵². There is however a "marginal cost" in that the hydro-electric power is easy to regulate and therefore can be "saved", at least within a season, until a higher price for electricity is paid.

great interest in encouraging such discussions.

SKN has held seminars on the ethics of the disposal of nuclear waste⁵³ and on the possibility of finding reliable answers to questions that are posed under a cloak of uncertainty⁵⁴. The social sciences also have a role in building up a knowledge base for decisions about how the waste will finally be disposed of. Studies on decision theory and risk analysis as well as sociological studies of scientific and political controversies are being funded. In addition, studies are being made of how it may be possible to transfer the knowledge about the waste disposal site to future generations, through for example, markers, myths or archives. Parts of the Swedish discussions on the ethics of nuclear waste handling have been reviewed in the introductory chapter of this thesis.

4.3 Proposals for the Disposal of Weapons-grade Uranium and Plutonium That Involve Using It in the Present Civil Nuclear Fuel Cycle

There have been a number of suggestions of how one should dispose of the fissile material left over when the superpowers' nuclear arsenals are being reduced. As is discussed below, it was very early recognized that the weapons-grade plutonium (WGPu) and weapons-grade uranium (WGU) in the nuclear warheads could be used for electric power generation if ever the nuclear weapons were to be destroyed. This is what we can call the most obvious and therefore most commonly suggested solution to the problem of how to dispose of the military fissile material. It is also a very enticing perspective for proponents of civil nuclear power as such solutions might, to a certain extent, improve the image of nuclear power in the eye of the public. In this chapter we deal with this type of suggestions. There are, however, many other suggestions of how to dispose of the military fissile material. These are discussed in Chapter 8 together with waste disposal solutions for civil high-level nuclear waste different from those described in the section above⁵⁵.

Let us first look back to the early history of nuclear energy. In his famous "Atoms for Peace Proposal" to the United Nations General Assembly on December 8, 1953, President Eisenhower put forward the following suggestion for what he called "joint atomic contributions"⁵⁶:

"I therefore make the following proposal:

The Governments principally involved, to the extent permitted by elementary prudence, to begin now and continue to make joint contributions from their stockpiles of normal uranium and

⁵³. The report from this seminar has been published as SKN (1988A) and an English summary as SKN (1988B).

⁵⁴. Reports from two such seminars have been published as SKN (1990A) and SKN (1991A).

⁵⁵. We are throughout the thesis concerned with long-term disposal solutions that make the material as difficult as possible to reuse in nuclear explosives. In an interim period, stockpiling the material is, of course, necessary. It may be tempting to make such stockpiling more or less permanent. This is, however, not an acceptable long-term disposal solution.

⁵⁶. The speech is reproduced in United States Congress (1980) and in Appendix C of Pilat, Pendley & Ebinger (1985).

fissionable materials to an International Atomic Energy Agency. We would expect that such an agency would be set up under the aegis of the United Nations." ... "The more important responsibility of this Atomic Energy Agency would be to device methods whereby this fissionable material would be allocated to serve peaceful pursuits of mankind." ... "A special purpose would be to provide abundant electrical energy in the power-starved areas of the world."

In 1953 there was no civil nuclear power production in nuclear reactors and therefore the fissile material stockpiles that President Eisenhower mentions are the nuclear weapon arsenals of that time. The proposal was as such not adopted by the international community, but it was a starting point for the path to international civil utilization of nuclear power. This utilization was then initiated with the conferences on the Peaceful Uses of Nuclear Energy in Geneva in 1955 and 1958 and the establishment of the International Atomic Energy Agency (IAEA) in 1956 and EURATOM in 1956-1957.

As the nuclear arms race continued to greatly increase the superpower's nuclear arsenals, independently of the general state of international relations, much effort was put by various movements into halting and reversing the race. Looking back, it seems that so much effort was put into this work, and success seemed so far away that the question of what to do when success eventually would come, seems to have eluded the planning of these movements. The problem of how to dispose of the military fissile material in nuclear weapons did not reach the agenda of most of them until the late 1980's. In particular, the signing of the treaty between the United States and the former Soviet Union on the elimination of their intermediate-range and shorter-range nuclear missiles in 1987 (the INF treaty)⁵⁷, which can be called the first nuclear disarmament treaty as nuclear weapons were actually to be eliminated, caused a surge of activity⁵⁸.

As the INF treaty was being negotiated during 1987, the interest for how to

⁵⁷ United States Department of State (1987).

⁵⁸ Some work was, however, done on the possibilities of destroying nuclear weapons before the subject was picked up in the late 1980's.

This author has studied the subject since 1982 when the Swedish Society for Engineers for the Prevention of Nuclear War was founded and the question was raised what to do with the nuclear warheads when disarmament would start. Short articles were published in the society's journal (Swahn 1984, Swahn 1987).

In 1978, on the eve of the signing of the SALT II accords, there was a paper presented on the subject at the 28th Pugwash Conference on Science and World Affairs (Hewitt et al. 1978). The authors foresaw that "an alternative is to use it in existing thermal nuclear reactors". In 1982 Simon Ramo in a couple of articles proposed that the bomb material should be converted to fuel for nuclear electric-power generators (Ramo 1982A, Ramo 1982B). One of these articles stimulated an article in a Swedish newspaper (Wikdahl 1982).

In 1983 John Taylor et al. wrote an unpublished report that included a wide range of possibilities for the destruction and disposal of both weapon-grade uranium and weapon-grade plutonium (Taylor et al. 1983). The report stated that for mainly economic reasons it would be preferable to use the material in the civil nuclear fuel cycles and proposed that such use would benefit the countries in the developing world. The main results of this report were later published (Taylor et al. 1985).

At approximately the same time, the Swedish journalist Fredrik Lundberg wrote on the subject (Grimwall & Lundberg 1984, Lundberg 1985) and A. De Volpi brought up the question in an article in 1986 (de Volpi 1986).

handle the fissile material from the dismantled missiles grew. Several studies have been published since, the most important being Amaldi, Farinelli & Silvi (1989), Taylor (1989)⁵⁹, Bloomster et al. (1990), Hebel (1990), Amaldi (1991), Donnelly & Davis (1991)⁶⁰, FAS (1991) and Harrison (1991)⁶¹.

Before we start to describe some of the proposals for the conversion of the military fissile material into the civil nuclear fuel cycle that surfaced at this time we can look at what actually was stated in the nuclear weapons reduction treaties between the United States and the Soviet Union that have been signed so far. In both the INF treaty and the START treaty of 1991⁶², there have been no special provisions made of what to do with the nuclear warheads or the fissile material in these. The warheads are to be removed before the missiles are destroyed or converted, but they are then returned to the stockpiles for storage or reuse. In fact, some of the United States warheads that were present on the Pershing II missiles eliminated according to the INF treaty, are being "repackaged" as B61 nuclear bombs⁶³.

We can also state that the destruction and dismantling of the nuclear weapon systems, as such, does not constitute a problem. The missiles and launchers covered in the INF treaty have been destroyed or converted⁶⁴. There will be no considerable problems in doing this also for the START treaty. It is possible that the missiles that are to be eliminated in START will to a larger extent be reused for satellite launches as the missiles are generally capable of carrying a greater load than those covered by the INF treaty⁶⁵. There have been concerns, however, that the destruction of missiles can have negative environmental effects⁶⁶.

In addition, the dismantling of the nuclear warheads does not represent a problem. The warheads in the arsenals are periodically taken apart and the plutonium is recycled in order to remove impurities that have collected due to decay. In addition, a large number of older warheads have been removed from the arsenals and dismantled in order to remove and reuse the components and materials in the warheads⁶⁷.

⁵⁹. Other, and later articles by this author on this subject are Taylor (1990A), Taylor (1990B) and Taylor & Feoktistov (1991).

⁶⁰. There is also an earlier report by Donnelly (1989), which the author has not been able to acquire.

⁶¹. Other articles on the subject are APN (1988), Nelson (1989), Farinelli & Silvi (1990), Hubbard (1991), Dyring (1991) Farinelli & Silvi (1991) Hayward (1991), Silvi (1991) and The Uranium Institute (1991).

⁶². United States Department of State (1991).

⁶³. See Norris & Arkin (1990).

⁶⁴. Most of the missiles were crushed or eliminated by explosive demolition or burning (see Wong 1988A, Wong 1988B, Kaldor 1988, Foley 1988). Some of the launch systems were converted into civilian systems. An example of conversion is the fitting of a crane for industrial use on a former Soviet SS-20 missile transporter-erector-launcher (see picture on page 30 in United States DOD (1989)).

⁶⁵. The possibility of using military missiles that are eliminated in arms reduction agreements as satellite launchers have been discussed in Deudney (1985), Florini & Potter (1988) and Florini & Potter (1990). In 1990 the United States Department of Defence were having plans to do this with missiles eliminated under the START treaty (Lawler 1990).

⁶⁶. See, for example, *Newsweek* (1989).

⁶⁷. Cochran, Arkin & Hoenig (1984, p. 40) states that in 1981 the average age of nuclear warheads in

We will not here discuss the exact mechanism involved when the weapons are to be removed from active service and how the fissile material is to be handled in interim storage awaiting destruction, i.e., the process steps for elimination. Possible dismantling and verification procedures and storage possibilities for the fissile material have been discussed and the reader is referred to, for example, Taylor (1989), Smith (1990) and FAS (1991).

As stated initially in this section, in this chapter we will instead concentrate on how the fissile material from dismantled nuclear weapons could be used in the present civil nuclear fuel cycle for electric power production. The materials concerned are weapons-grade plutonium (WGPu) and weapons-grade (highly-enriched) uranium (WGU). As discussed in Chapter 5 there are about 233 tonnes of WGPu and 1 100 tonnes of WGU to dispose of if the fissile material from all nuclear weapons in the global nuclear arsenals is to be disposed of.

Weapons-grade uranium has a ^{235}U content of about 93%. Most civil nuclear power reactors are fuelled with low-enriched uranium ($\approx 3\%$ ^{235}U). It is possible to mix the WGU from dismantled nuclear weapons with natural uranium or even depleted uranium in order to make fuel for these reactors. A rough calculation gives that 1 tonne of WGU corresponds to the fuel needed in an electric generating capacity of 1.36 GW_e in light-water reactors for 1 year if it is mixed with natural uranium⁶⁸. This means that 1 100 tonnes of WGU would be able to fuel a capacity of

the United States stockpile was 12 years. They state that this suggests that approximately 4% of the existing inventory is retired annually, which is equivalent to approximately 1000 warheads per year or about 3 per day.

$$\begin{aligned}
 P_e &= \alpha \cdot \delta \cdot m_U \cdot P_U \cdot \frac{\beta}{\gamma} \cdot \frac{\eta}{\varepsilon} \\
 &\approx 0.93 \cdot 1.27 \cdot 1 \cdot 2.58 \cdot \frac{0.76}{1.17} \cdot \frac{0.33}{0.67} \cdot 1.40 = 1.36 \text{ GW}_e \quad \text{where}
 \end{aligned}$$

P_e = electric generating capacity possible to fuel

α = enrichment grade of WGU = 93% = 0.93

δ = factor compensating for uranium-235 already existing in natural uranium, i.e. the enrichment is only raised from 0.7% to 3.3% = 1.27

m_U = mass of WGU = 1 tonne

P_U = continuous power released from fission *all nuclei* of pure ^{235}U for one year = 2.58 GW_{th} per tonne

β = percentage of uranium-235 fissioned before spent fuel is removed (3.3% enrichment original, 0.8% enrichment in spent fuel, 33 000 $\text{GW}_{th}\cdot\text{days}\cdot(\text{kgU})^{-1}$ burn-up) = 76% = 0.76

γ = loss of uranium-235 nuclei due to neutron capture = 1.17

η = efficiency of conversion thermal to electric = 0.33

ε = utilization factor (average capacity factor) for the electricity generating station = 0.67

f_{Pu} = factor taking into account energy from fission of plutonium produced in core = 1.40

Data are primarily from Choppin & Rydberg (1980).

We can compare our value with those estimated or calculated by others. Taylor (1989) estimates that 1 tonne of ^{235}U can be used as fuel in a 1 GW_e nuclear plant for approximately one year. At 93% enrichment and mixing with natural uranium this would give a P_e of about 1.37 GW_e , close to our calculated value. FAS (1991) states that about 800 kg of ^{235}U in low-enriched (3-4% ^{235}U) uranium will fuel a 1 GW_e plant for about a year at 65% average capacity factor. Amaldi (1991) reaches a slightly higher value (1.6 GW_e capacity for 1 year) in a similar calculation but he does not take into account that some of the uranium-235 is left in the spent fuel, nor that some uranium-235 is lost due to neutron capture. The first "approximation" would actually be the true if continuous reprocessing and recycling of the uranium was carried out.

Choppin & Rydberg (1980) state that on an average a 1 GW_e light-water reactor power station

1 500 GW_e for 1 year. As shown in Chapter 5, the present global electric nuclear power generating capacity is about 325 GW_e and can be estimated to peak at approximately 380 GW_e . This means that the WGU would be able to fuel the world's nuclear power generating reactors for approximately 4-5 years⁶⁹.

The civil nuclear power reactors that are not using natural or low-enriched uranium as fuel use what is called mixed-oxide (MOX) fuel. In such fuel, reactor-grade plutonium from reprocessed spent civil nuclear power reactor fuel is recycled is mixed with natural uranium, reprocessed uranium or uranium tailings from uranium enrichment plants. Such MOX-fuel rods are in a core often mixed with ordinary low-enriched uranium fuel rods, so as to achieve similar characteristics (reactivity, etc.) compared to a reactor fuelled with low-enriched uranium⁷⁰. It would be possible to replace the reactor-grade plutonium with WGPu from the destroyed nuclear warheads. Taylor (1989) states that the yearly loading rate in a MOX-fuelled 1 GW_e reactor is 350 kg of plutonium. In addition 670 kg of ^{235}U is used. This means that the 233 tonnes of WGPu in the worlds nuclear arsenals could fuel approximately a 665 GW_e generating capacity for one year, or the global electric nuclear generating capacity for about 2 years if only MOX-fuel were used in the world's nuclear power reactors.

A second possible use for the WGPu in the present civil nuclear fuel cycle is as fuel in the cores of fast breeder reactors (FBRs). The French Superphénix FBR is rated at a net electricity generation capacity of 1 200 MW_e and would consume approximately 2.2 tonnes of WGPu per year⁷¹. Approximately the same amount of WGPu would, however, be produced in the reactor's breeding blanket if such a blanket was used.

How feasible would it be to, in reality, use the military grade fissile material as described above? Let us first consider WGU. There is a well-developed industry for the production of low-enriched uranium (LEU) fuel. It is difficult to see that, technically, these facilities could not be converted to mixing WGU with natural uranium to produce LEU fuel. There are safeguard concerns that have to be addressed, but these should not be unreasonably difficult to solve. It is evident that if this solution is chosen, then the need for civil uranium enrichment would radically decrease for several years. If the WGU is to be used for fuel in civil nuclear power reactors the present LEU fuel industry would be severely affected.

consumes 2.2 kg of uranium-235 per day. Using a figure of 93% enrichment of the WGU, mixing with natural uranium, and that 24% of the uranium-235 is left in the spent fuel, this corresponds to a value for P_e of 1.44 GW_e , i.e., slightly higher than our calculated figure.

⁶⁹. The values of electricity generating capacity used in the scenario in Chapter 5 are the net values, i.e., the amount of electricity that can be delivered to the grid when the electricity needed to power the generating plant has been subtracted from the gross electricity generating capacity. The calculation done in the previous note actually gives the gross value, but these are usually around 5% above the net value and therefore make a relatively small difference.

⁷⁰. In IAEA (1991B, p. C31) it is stated that it has been demonstrated that MOX can be used safely in existing LWRs up to a fuel loading of 30% MOX–70% UO_2 without any need for significant modification of reactor control systems.

⁷¹. Flowers (1983, p. 44) states that the plutonium feed to a 1 000 MW_e FBR would be about 2.8 tonnes per year (100% availability). The value given in the text is for 1 200 MW_e and 65% availability.

For several reasons, it is less feasible to use the WGPu in MOX-fuel compared to the WGU in LEU fuel.

First, the infrastructure for MOX-fuel recycling is not as widely spread⁷². Of special importance is that MOX-fuel recycling is very little developed in the United States.

Second, there is a great lack of capacity for MOX-fuel fabrication⁷³. New facilities would have to be constructed if the WGPu were to be used in this manner.

Third, there are safeguard problems when using WGPu as nuclear reactor fuel that would prevent a global use.

If one finally considers FBR use of the WGPu, there is very little capacity for such use. The Superphénix, the only reactor that would be able to absorb a larger amount of WGPu as fuel, has been plagued by technical difficulties. In addition, the economic reality of the cost of FBR recycling of plutonium has also reached the French nuclear programme. The Superphénix has been shut down and it is unclear if it will be restarted.

This means that presently the only military fissile material that can reasonably be used in the civil nuclear fuel cycle is the WGU. Taylor (1990) estimates that if all the WGU were to be used as low-enriched fuel in light-water reactors, the value of each kg of ²³⁵U would be USD 38 000 and the total value of the WGU in the global military stockpiles would be USD 38.9 billion, assuming 93% uranium-235 in the WGU.

As the present cuts in the nuclear arsenals of the United States and the former Soviet Union are continue, large stockpiles of WGPu and WGU are built up. There is therefore a need for interim solutions for storage of the material while awaiting decisions on what should be done in the longer term. The United States is giving economic aid to the former Soviet Union so that storage facilities can be constructed for its stockpiles⁷⁴. In a longer term there is perhaps a role for the International Atomic Energy Agency (IAEA) to play here as an agency that keeps accountancy of the stocks of excess military fissile material. Such a role might also facilitate any use of the WGU (or WGPu) in the civil nuclear fuel cycles. This is discussed a little further in Chapter 9.

One can perhaps add here that, if one accepts the problems of using WGPu in

⁷². There are presently MOX-fuel fabrication facilities in Belgium, France, Germany and Japan. There is also a MOX-fuel fabrication plant under construction in the UK (IAEA 1991B, pp. C31, C44). There is no MOX-fuel fabrication plant in the former Soviet Union (Bukharin 1991).

⁷³. The present total MOX-fuel fabrication capacity is 95 tonnes of HM per year, using approximately 4.3 tonnes of plutonium per year. The total amount of plutonium being recovered in reprocessing is between 10 to 15 tonnes per year, depending on how one counts, and could thus sustain a MOX-fuel fabrication of around 330 tonnes of HM per year (Albright and Feiveson 1992, p. 80, IAEA 1991B, pp. C30-C31, C34, C44). This means that present MOX-fuel fabrication facilities can only handle about one third of the annually reprocessed plutonium. The projected plutonium requirement for MOX-fuel only reach 12.6 tonnes of plutonium per year in 2005, so the situation will not improve in the near future (IAEA 1991B, p. C44). In addition the stockpiles of reprocessed civil reactor-grade plutonium have reached 125 tonnes, of which 60 tonnes is plutonium from light water reactors (Albright 1991). There is therefore no possibility for the present global nuclear fuel cycle to absorb all the WGPu without the construction of new facilities.

⁷⁴. Paine & Cochran (1992).

the civil nuclear fuel cycle, or separated RGPu for that matter, then the next possibility that comes to mind is to be to mix the WGPu and the RGPu with high-level reprocessing waste or spent nuclear fuel and then dispose of it as spent nuclear fuel. There are practical problems with this, but the solution is in principle possible.

4.4 Plans for Disposal of Military High-level Nuclear Reprocessing Waste

The HLW from the military weapons-grade plutonium production facilities of the nuclear weapon states is very similar to reprocessed HLW from the civil programmes. The HLW is a result of the reprocessing of spent "fuel" from plutonium production reactors. The plutonium is removed and is used in nuclear explosives, the uranium is recycled as new fuel and the remaining actinides and fission products have approximately the same composition as civil reprocessed HLW.

In nuclear weapon states where the military and civil nuclear programmes are connected, for the use of certain facilities, it is normally not a problem to dispose of the military HLW. The amounts of military HLW are most often much smaller than the corresponding amounts of civil HLW. This is true for France, the Soviet Union and the United Kingdom⁷⁵. In these cases, the military HLW will be disposed of in a similar manner as the civil HLW. China has close links between the military and civil nuclear programmes but has, at least for the present, produced no civil HLW. In this case the HLW disposal programme will be foremost a military one^{76,77}. In the case where the military and civil nuclear programmes are separated, as in the case of the United States, the situation is more complex and it could in such a situation be possible that a separate waste disposal system had to be built for military nuclear waste. It would, however, seem likely that economical considerations will lead to the development of a common HLW disposal system for the two programmes in such cases and this will be the case in the United States.

In the United States, since the late 1980's, the military nuclear complex has come under intense scrutiny. During the 50 years that the complex has operated, the operations of the plants and the handling of nuclear wastes has caused widespread radioactive contamination of the areas surrounding the sites⁷⁸. The total clean-up costs for this contamination, not all of it radioactive, has been estimated to be as high

⁷⁵. Of the emerging nuclear weapon states, India is in a similar situation.

⁷⁶. However, China is presently launching a civil nuclear power programme and the country has presented offers to dispose of foreign civil HLW at a future HLW disposal site.

⁷⁷. Of the emerging nuclear weapon states, Israel is in a similar situation. Israel has no civil nuclear power programme, but has produced large amounts of military HLW while carrying out reprocessing at the Dimona site.

⁷⁸. See, for example, Lawless (1985), GAO (1986), Marshall (1986), Alvarez & Makhijani (1988), Crawford (1988), Steele (1988), Abas (1989), Shulman (1989A), Shulman (1989B), Steele (1989A), Steele (1989B), Albright et al. (1990), Saleska & Makhijani (1990), *Arms Control Today* (1991) and *Bulletin of the Atomic Scientists* (1991).

In addition, an Office of Technology Assessment report from February 1991 provides a detailed analysis of the problem (OTA 1991).

as 100 to 200 billion USD (Crawford 1988, Shulman 1989B, *Arms Control Today* 1991). In 1989, a five-year USD 19.6 billion environmental clean-up plan was announced by the United States Department of Energy (Shulman 1989B)⁷⁹. A recent revised 5-year plan from the DOE estimates the costs for this period to USD 38 billion, with estimates that the whole cleanup may take 30 years and cost USD 100 billion⁸⁰.

The military HLW is part of this environmental problem. The liquid HLW that has been a by-product when reprocessing the spent fuel from the military plutonium production reactors at the Hanford and Savannah River sites has been stored in large underground steel tanks. The tanks now contain a mixture of liquids, salt and sludge. Military HLW from the Idaho Chemical Reprocessing Plant is stored in the form of a powder.

The Savannah River site holds about 55% of the United States military HLW, if one counts by activity content (about 128,000 m³ containing 2.45·10¹⁰ GBq). It is stored in 51 tanks, about half of them single-walled which are being rapidly replaced because of leakage. Ten tanks have leaked so far, four of them significant amounts (Marshall 1986, Wicks & Bickford 1989, OTA 1991).

At Hanford there is 244 000 m³ (containing about 1.65·10¹⁰ GBq) of military HLW in 149 single-shelled tanks and in 28 newer double-shelled tanks. At least 66 of the single-shelled tanks leak (Shulman 1989A, Steele 1989A, Saleska & Makhijani 1990, OTA 1991). There is also some 11 000 m³ (2.5·10⁹ GBq) of calcine, a dried powder, at the Idaho Chemical Reprocessing Plant (Wicks & Bickford 1989, OTA 1991). Much of the contamination clean-up costs is a result of leaking tanks at Savannah River and Hanford.

In preparation for final disposal of United States military HLW, several vitrification facilities are being built. In the tanks, the sludge and salts contain most of the HLW, a result of a neutralization of the initially very acidic liquid waste with sodium hydroxide. The sludge and salts are processed and the HLW is then vitrified. A facility is being built at Savannah River to be completed by 1992, a facility at Hanford is to be operating by the late 1990's (Wicks & Bickford 1989, Smith, Nyman & Anderson 1989)⁸¹. The vitrified HLW is then to be disposed of together with the United States civil HLW.

In the Soviet Union the military HLW problem also appears to be very large. In a recent report and article Cochran & Norris (1991A, 1991B) indicate the magnitude of the Soviet military HLW problem. As an example, the liquid HLW from the Chabalinsk-40 (or Kyshtym) complex⁸² was for two years, before September 1951,

⁷⁹. It is uncertain whether this sum will actually be spent. The United States administration has for example suggested that the 1992 spending should be cut by 1.5 billion from the planned 5.7 billion (*Bulletin of the Atomic Scientists* 1991, p.38).

⁸⁰. *Arms Control Today* (1991).

⁸¹. A facility for vitrifying the relatively small amount of civil HLW produced at the West Valley, NY, commercial reprocessing plant is to be completed by 1992. There is 2 130 m³ (1.1·10³ GBq) of civil HLW at this site (OTA 1991, p. 46-47). A facility to consolidate the HLW at the Idaho Chemical Reprocessing Plant will start operating by about 2011 (Wicks & Bickford 1989).

⁸². This complex was the first military plutonium production complex built in the Soviet Union. Since 1978, the reprocessing plant at this site has been used for reprocessing of civil spent fuel and spent

fed directly into the Techa River. The Techa River is now cordoned off with a wire fence. Reservoirs have been built to hinder contaminated water from flowing downstream and into the Arctic Sea. Between September 1951 and 1953, the liquid HLW from Chabalinsk-40 was instead fed into an open marsh, Lake Karachay. Since 1953 intermediate-level nuclear waste has continued to be released into the marsh. The lake, which now has a volume of 400 000 m³, containing 4.4·10⁹ GBq of activity. Radiation levels at the shore of the marsh near where the wastes are discharged are reported to be about 600 R·h⁻¹⁸³. The surface radiation exposure level of the lake is otherwise about 3-4 rad·h⁻¹ (30-40 mGy·h⁻¹).

The circumstances surrounding the military HLW handling at the Tomsk-7 plutonium production complex is less known but there are indications that the situation may be similar.

naval propulsion reactor fuel. The spent fuel from the military plutonium production reactors at the site has been reprocessed at the Tomsk-7 complex.

⁸³. In this case, 600 R·h⁻¹ would represent a whole body dose to a person standing at the shore of approximately 6 Sv·h⁻¹. The lethal whole body dose (LD_{50/30}) for a human being is approximately 3-6 Sv, depending on the general health status of the person and the medical treatment given (see, for example, Hall (1978)). This means that a lethal dose would be received in an hour by a person standing unprotected on such a spot.

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PART II

THE LONG-TERM
NUCLEAR EXPLOSIVES
PREDICAMENT

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5. THE PRODUCTION OF MILITARILY USABLE FISSILE MATERIAL: A QUANTITATIVE SCENARIO FOR A POST-NUCLEAR WORLD

In the review chapters we have discussed the question of how militarily usable fissile material is produced and which type of material can be used for the construction of nuclear explosives, as well as some of the "present planning" for the disposal of militarily usable fissile material. In this chapter a scenario is constructed to provide a stage for the study of the long-term problems that concern the handling of military and civil fissile material that is usable for the construction of nuclear explosives, what we shall later call the long-term nuclear explosives predicament.

In the introductory chapter we have discussed the question of whether nuclear power can be considered to be a long-term sustainable source of energy. We found the answer to this question to be negative. The consequence of this for the planning of the handling of long-lived waste in the form of spent fuel, separated reactor-grade plutonium as well as for military fissile material is discussed later in the thesis, but in this chapter we will construct a quantitative scenario for approximately how much fissile material this generation may leave for future generations living in a "post-nuclear world"¹. By necessity the scenario gives quite a rough estimate of the amounts involved, but, as is shown later in this chapter, strong arguments can be given for the claim that the scenario is realistic.

In the scenario we divide the nuclear material that is to be studied into two main categories, material that is mainly civil in origin and material that mainly has a military origin. In the first case we discuss the amounts of spent fuel produced in nuclear reactors, and the amounts of reactor-grade plutonium (RGPu) in this fuel. We also give estimates of how much of this plutonium has been separated in civil reprocessing. In the second case we discuss the amounts of weapons-grade plutonium (WGPu) and weapons-grade uranium (WGU). In the case of WGU there is some civil use², but all WGU, whether it comes from the burnt-out cores of civil research reactors, from dismantled nuclear weapons or from burnt-out cores of military naval propulsion or space reactors, is treated together as military WGU, because of its direct military potential for use in nuclear explosives.

¹. At the risk of being repetitive, it is once again here stated that a future "post-nuclear world" is not a world that does not use nuclear technology, but rather a world that does not use large-scale nuclear technologies, civil or military, which produce large amounts of long-lived high-level nuclear waste. A post-nuclear world, in this sense, would still have to take care of the waste from the nuclear power/nuclear weapons era and therefore would need to use nuclear technology for this purpose. In addition, nuclear technology for medical and other purposes would, of course, be used but would not rely on radionuclides from technologies that produce large amounts of long-lived waste, or, if this is necessary, would bear the costs of nuclear waste handling from the types of solutions discussed in Chapter 8.

². As discussed briefly in Chapter 2, when WGU is used for other purposes than in nuclear explosives, it is normally referred to as highly-enriched uranium.

5.1 Assumptions for the Scenario

The following main assumptions are the basis for the scenario:

- There are no new orders for civil nuclear power plants. The nuclear power plants that are presently commercially operated are utilized for a 40-year operating life. The nuclear power reactors that are under construction and have a planned date for start of commercial operation are put in service at that date and are utilized for a 40-year operating life.
- The production of new fissile material for the nuclear weapons arsenals is discontinued.
- The use of highly-enriched or medium-enriched uranium in civil nuclear research reactors and military naval propulsion and space-based reactors is slowly phased out³.

Looking fifty years into the future this scenario leads to a world in which there is no new production of spent fuel from civil reactors or in nuclear weapons programmes, a post-nuclear world. A scenario based on the stated assumptions allows an estimate of the total amount of militarily usable fissile material that has to be managed, treated and disposed of, either by the present generation of world inhabitants or by future generations.

It can be noted here that in the post-nuclear world militarily usable fissile material may still be produced in small amounts. However, intense care will be taken to dispose of it as waste in appropriate ways, and the costs for this will be taken into account when choosing a technical process that produces such material and other long-lived radioactive waste.

5.2 The Future of the Civil Nuclear Power Programme

It is possible to use data from the International Atomic Energy Agency (IAEA) to make an estimate of the amount of RGPU that has been produced in the world civil nuclear power reactors as well as to make an estimate of how much will be produced in the future in the scenario described above. The IAEA Power Reactor Information System is a data base on the world's nuclear power reactors. The reactor characteristics and operating experience of nuclear power reactors in operation, shut

³. The time scale for such a phase-out could be more specifically specified, but it is quite difficult to make any direct forecast.

It is unfortunate that the present changes in the global world order do not immediately mean that nuclear-propelled ships and submarines are much less 'necessary' for the major powers to have access to, even though cut-backs will probably soon be seen here too. On the other hand, the reactors, while operating on WGU, actually reduce the amounts of directly militarily usable material. They are, on the other hand, a nuclear safety and environmental concern. See, for example, Arkin & Handler (1989) for a discussion of the risks for accidents with nuclear reactors on board ships and submarines. Space-based reactors are also an environmental hazard, and there are suggestions that they should be banned for all space missions except for those into deep space. See, for example, Aftergood et al. (1991).

down or under construction are published each year⁴. Using the latest edition of this publication (IAEA 1991A) a data base was constructed that included:

- The IAEA-code, name, reactor type and present (or planned) net electricity generating capacity for nuclear power reactors that either:
 - a) have ever been commercially operated, or
 - b) were under construction with a planned date for completion⁵
- The year of construction start.
- The year of start of commercial operation for reactors that have been completed and connected to the grid.
- The year for planned commercial operation for reactors still under construction.
- The shut-down year for reactors that have been shut down.
- Estimated year for shut-down for all other reactors, 40 years from actual or planned commercial operation⁶.

All in all, there are 550 reactors in the IAEA statistics for nuclear power reactors

⁴. In the data base a specific code is given to each nuclear power reactor that has been planned in the world. Planned reactors that have been cancelled, either before or after construction has started, are mentioned only in the editions of the publication prior to and including the year that the cancellation has taken place. In earlier editions of the publication planned reactors are included in the statistics, but after the 1988 edition they are not.

⁵. The only exception to this is in the case for the former Soviet Union where no dates for completion are given for any reactors under construction but where the official policy seems to have been that nuclear power as an energy source is to be used also in the future. An estimated time for completion of 6 years is used in this scenario for Soviet reactors under construction, a time that has been common during the end of the 1980's (IAEA 1991A, p. 11). This actually means that a few reactors that are not connected to the grid in 1987 through 1990 were in our scenario counted as being connected (see Appendix 2). There is therefore a small discrepancy between the scenario and data for actually connected reactors for these years.

There were two possible alternative ways to deal with this problem, if one wants to include these reactors in the scenario. First, one could have added them all at one year, say 1992, but this would give a sharp rise in capacity in just one year which would be equally inaccurate. Second, one could have made a new estimate for a longer mean construction time, but such an estimate would only be a guess and would not build on any data.

⁶. The variation of the scenario with the choice of lifetime is shown later in this chapter.

The use of an estimated lifetime of 40 years is consistent with the use of this estimate in the annual report on the prospects for commercial nuclear power in the United States and the world issued by the United States Energy Information Administration of the Department of Energy (United States DOE 1990). The decision to use a 40 year life-span in some of the scenarios created in this report is in turn based on the fact that the United States Atomic Energy Act of 1954, that provides the original set of regulations for nuclear power plant licensing in the United States, sets a statutory limit of 40 years for the duration of licenses. In United States DOE (1990, p. 14) it is stated that "the selection of a 40-year limit was not based on the anticipated useful life of the nuclear plants but rather on financial and economic considerations".

It is, of course, possible to choose another life-span for the nuclear plants. The Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD) has in a report used 30 and 25 years as lifetimes for their comparison of the economics of nuclear versus coal power plants (OECD/NEA 1989). The report includes a table (OECD/NEA 1989, p. 66) where the amortization life and technical life of nuclear power plants of several OECD countries as used in their national economic calculations are given. The estimates of the technical lifetimes vary from 30 to 50 years.

If one studies the mean lifetime for nuclear power reactors already shut down using IAEA data (IAEA 1991A, pp. 42-44), one finds that they have been connected to the grid for an average of 17.6 years. Because many of these reactors were of an early design and some were shut down for other than technical reasons, such a figure might be low as an estimate for future technical lifetimes of reactors.

that in principle qualify for inclusion in our scenario⁷. The types and numbers of reactors are shown in table 5.1. In our scenario we have, however, neither included the 11 Fast Breeder Reactors (FBRs) nor the 11 reactors of "other" type⁸. The FBRs that have been constructed have mainly been experimental or demonstration plants, but are still included in the IAEA data⁹. The same comment applies to the "other" reactors in the data base which are of various designs. These reactors are prone to have relatively low load factors and short lifetimes. The inclusion of these reactors in the scenario would result in an overestimate of the civil fissile material production calculated using the scenario¹⁰.

Reactor type	Number of reactors
Reactors included in the scenario	
Light water reactor (LWR)	403
Heavy water reactor (HWR and PHWR)	49
Gas-cooled reactor (GCR)	37
Light-water/graphite reactor (LWGR)	27
Advanced gas-cooled reactor (AGR)	15
Total included	531
Reactors not included in scenario	
Fast breeder reactor (FBR)	9
Others	10
Total not included	19
Overall total	550

Table 5.1. Number of reactors in the IAEA statistics

Figure 5.1 shows the estimated number of civil power reactors, according to the scenario, that are connected to the grid each year from 1950 to 2050. The first

⁷ A listing of these reactors, and relevant data for the reactors, is appended as Appendix 2.

⁸ These are high-temperature gas-cooled graphite-moderated reactors, heavy-water-moderated gas-cooled reactors, heavy-water-moderated boiling light-water-cooled reactors, and a steam-generating heavy-water reactor.

⁹ The fast breeder reactors are part of the plans for recycling of plutonium from spent fuel from nuclear power plants and therefore use RGPu as fuel. As discussed in Chapter 4, most such schemes have been deferred and many countries are now planning for direct disposal of spent nuclear fuel. France has had the most advanced plans for recycling plutonium in FBRs but the worlds only full-scale FBR, the French Superphénix, is currently not operating and it is unclear whether it will be restarted again.

¹⁰ In addition this relieves us of the problems that are involved with the calculation of plutonium consumption and production in the FBRs in such a scenario. Similarly, we have not included the use of MOX-fuel in the scenario.

reactor that IAEA considers a nuclear power reactor was put on line in 1956¹¹ and in this scenario the last reactor is expected to be shut down in 2039¹².

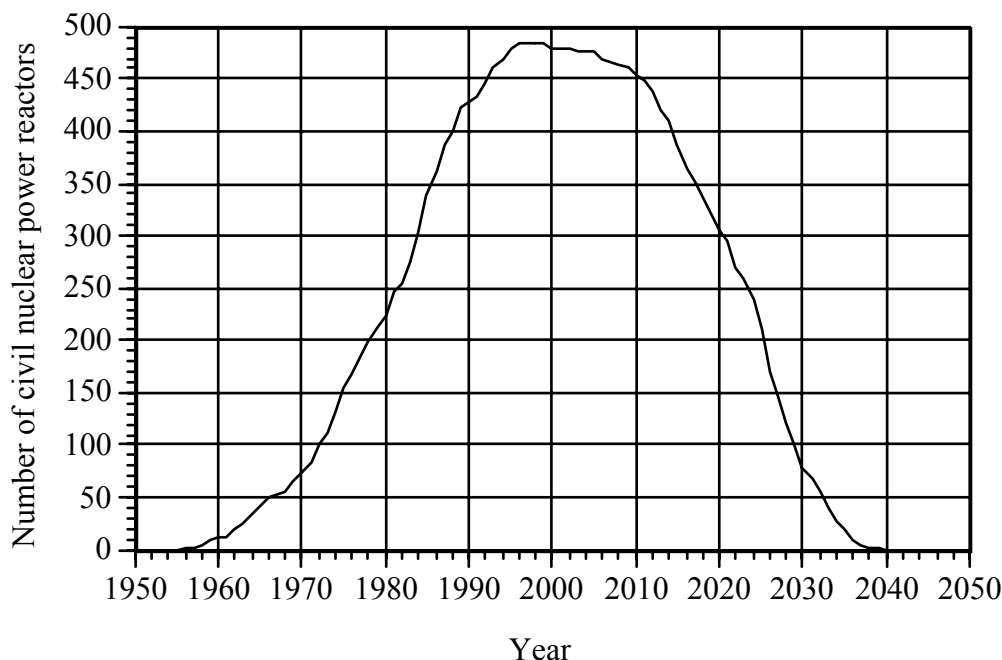


Figure 5.1. The global yearly total number of civil nuclear power reactors

As can be seen in the figure, the number of operating civil nuclear power reactors in the scenario has increased steadily until the present and will continue to increase until the end of the 1990's when a plateau is reached. There is then a slight, but steady, decline in the number of reactors until about the year 2010 when the number starts to decrease more rapidly. The last reactors are taken out of use in the late 2030's.

The data base also contains the net electricity generating capacity of the power plants. In figure 5.2 the annual total net generating capacity of all the world's civil nuclear power reactors is presented from the year 1950 to 2050 according to the scenario. Many power reactors have their capacity increased slowly over the years as improvements in the construction are introduced. Because the present capacity is utilized for calculations of total capacity for years earlier than 1990, a slight overestimate of the total capacity in those years is inherent in the data in figure 5.2. At the same time it is possible that, for the same reason, the values for the year 1991 and forward are underestimating the true capacity.

As can be seen in the figure, the civil nuclear power capacity in the scenario

¹¹ This is the British Calder Hall Unit A.

¹² This is the Romanian reactor Cernavoda 5 the construction of which was started in 1986 and which, according to the IAEA statistics, is expected to be completed in 1999. The likelihood of the completion of the construction of this reactor may perhaps be questioned. Construction of the first Romanian reactor was started in 1980 and has yet not been completed.

peaks a few years after the number of power reactors has passed its maximum and the plateau is extended compared to the number of reactors. This is because, in general, new reactors connected to the grid have a greater power generating capacity than the older reactors being retired. As in the case of the number of reactors the generating capacity starts to decline rapidly after the year 2010 and reaches zero in 2039.

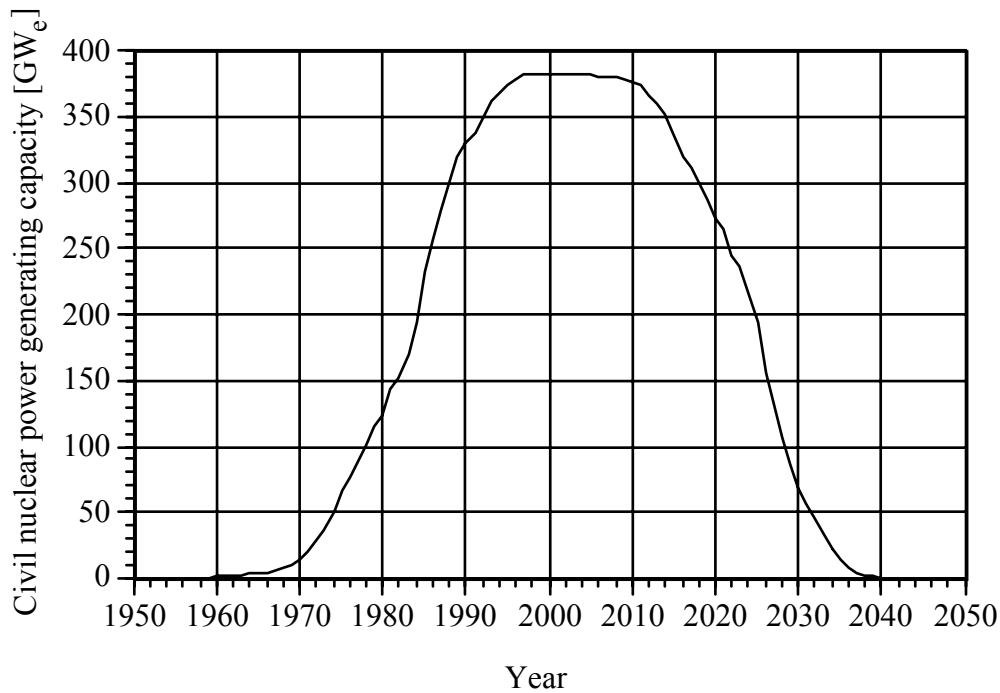


Figure 5.2. The total yearly power generating capacity of the world's civil nuclear power reactors

In figure 5.3 the total global nuclear electric generating power capacity per year is added with the previous year and presented as an accumulated value. This value, with the unit GW_e-year, is often used as a basis for discussions on how much nuclear waste or other material is produced in a reactor. As can be seen in the figure, there is an almost constant increase in the accumulated power generating capacity from the early 1980's until the middle 2020's. The function, of course, reaches its final value in 2039.

The information represented in figure 5.3 can be used to estimate how much RGPu has been and will be produced globally in the world's nuclear power reactors according to the scenario. This is attempted in the following sections.

Before concluding this section, some comments should be made on the dependency of the scenario on the choice of reactor lifetime, which we have taken to be 40 years. Figure 5.4, 5.5 and 5.6 show how the number of nuclear power reactors, the nuclear power generating capacity and the accumulated nuclear power generating capacity would vary if 25, 30, or 35 years were chosen, instead of 40 years, as the reactor lifetime.

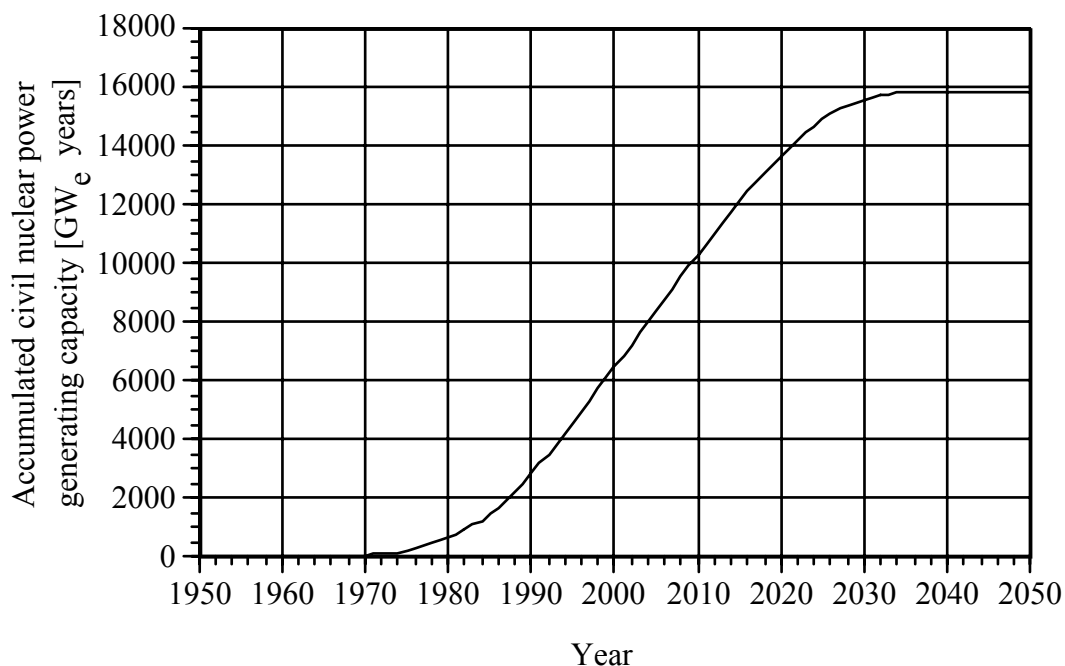


Figure 5.3. Accumulated global civil nuclear power reactor generating capacity

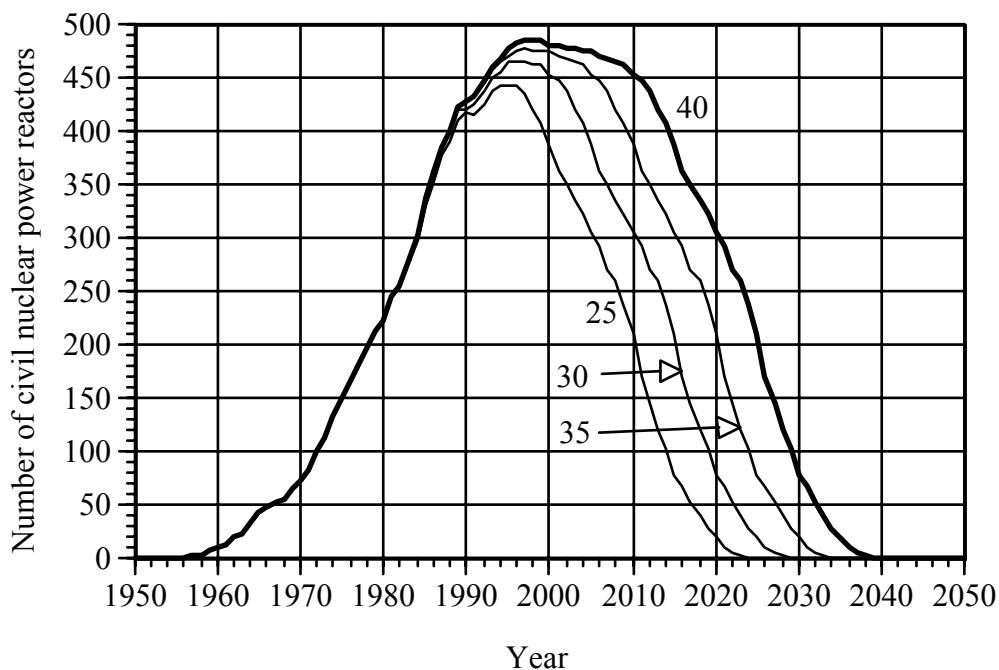


Figure 5.4. Variations in the number of reactors in the scenario with choice of reactor lifetime

If a shorter lifetime is chosen for the reactors that have not yet been shut down, the number of civil nuclear power reactors starts to fall earlier as seen in figure 5.4. In the case of the 25 year lifetime, the peak for the number of reactors is reached already in 1995 and the last reactor is shut down in 2025. The variations in nuclear

power generation capacity are similar, as shown in figure 5.5.

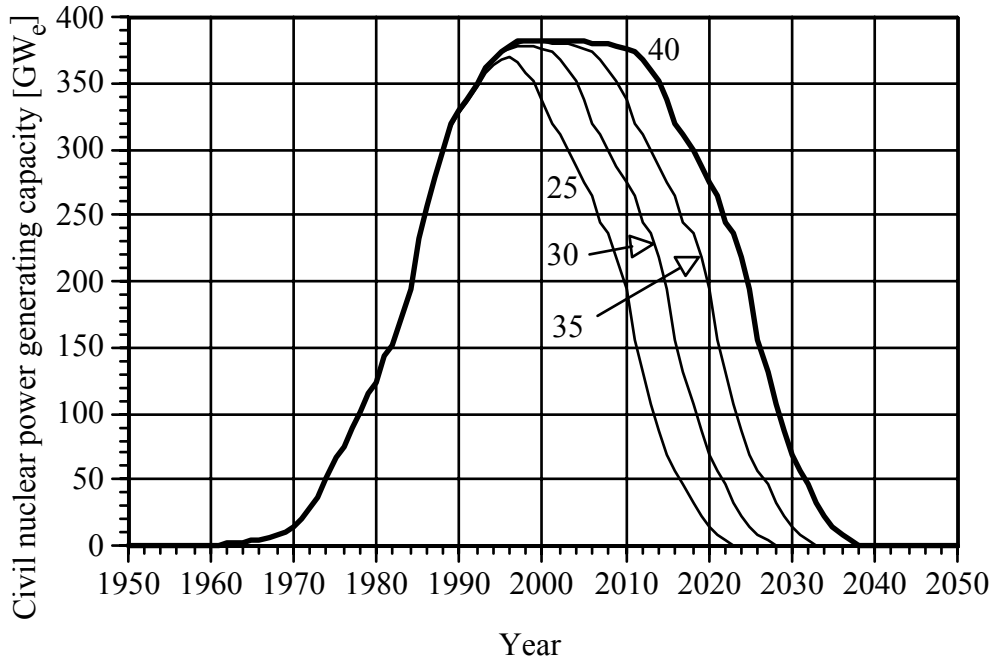


Figure 5.5. Variations in the nuclear power generating capacity in the scenario with choice of reactor lifetime

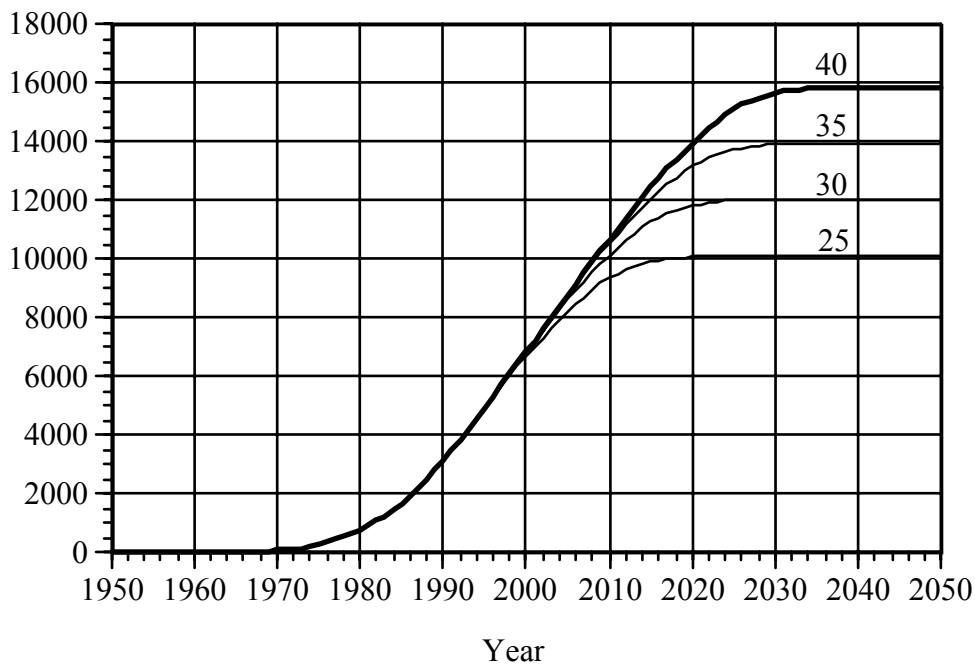


Figure 5.6. Variations in the accumulated nuclear power generating capacity in the scenario with choice of reactor lifetime

The most interesting figure is perhaps figure 5.6, as we will use the accumulated nuclear power generation capacity for the calculations of the amount of plutonium produced in the scenario. As we can see, there is quite a large variation in the final value reached, depending on the reactor lifetime chosen. The value for 40 years is 60% higher than that for 25 years.

5.2.1 *The Production of Reactor-grade Plutonium*

In Chapter 2 the production of plutonium in nuclear reactors was discussed. We discussed the difference in plutonium isotope composition between WGPu, produced in special military reactors, and RGPu, produced in civil nuclear power reactors. We will now attempt to make an estimate of the RGPu produced in the nuclear power reactors in our scenario.

Table 5.2 shows the different types of civil nuclear power reactors included in the scenario. As can be seen, the light-water reactors (LWR) dominate strongly¹³. Second comes the heavy-water-moderated reactors (HWR)¹⁴. These are then closely followed by the gas-cooled and graphite-moderated reactor (GCR) used almost exclusively in the United Kingdom and the Soviet light-water cooled graphite-moderated reactor (LWGR)¹⁵. Finally, the advanced gas-cooled and graphite-moderated reactor (AGR) is an improved version of the GCR and is exclusively used in the United Kingdom.

Reactor type	Number of reactors	Fuel	Coolant/Moderator
LWR	403	low-enriched uranium	light water/ light water
HWR	49	natural uranium	heavy water/ heavy water
GCR	37	natural uranium	gas/graphite
LWGR	34	slightly enriched uranium	light water/graphite
AGR	15	slightly enriched uranium	gas/graphite

Table 5.2. The types of civil nuclear power reactors in the data base for the scenario with information on fuel, cooling and moderator

Table 5.2 also includes data on the fuel type, the coolant and moderator systems of the different reactor types. It is beyond the scope of this discussion to go into the

¹³. These can be of two types, pressurized water reactors (PWRs) or boiling water reactors (BWRs).

¹⁴. Some of the heavy water reactors are pressurized.

¹⁵. The reactor involved in the Chernobyl accident was of this type.

details of the reactor technology that is decisive in the choice of these materials, but the fuel composition and reactor design influence the amounts of plutonium and isotope composition of the plutonium in the spent nuclear fuel from the different reactor types.

This means that all plutonium commonly called RGPu, because of differences in fuel composition and burn-up, does not have the same plutonium isotope composition. As was shown in figure 2.10 the isotopic composition of the plutonium in the burnt-out fuel varies with the burn-up level of the spent fuel, i.e., the time that the fuel has spent in the reactor¹⁶. In addition, the plutonium isotope composition indirectly depends on the isotopic composition of the uranium in the original fuel, i.e., the enrichment grade of the uranium. This is because a higher enrichment level allows the fuel to be used to a higher burn-up. In table 5.3 the isotopic composition of plutonium produced in the most common types of civil nuclear reactors is presented. For comparison the isotopic composition of WGPu is also included in the table.

Reactor type	Mean fuel burn-up [MW _{th} ·days·(kgU) ⁻¹]	Isotopic composition [%]					
		Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	
LWR PWR*	33 000	1.4	56.5	23.4	13.9	4.8	
	43 000	2.0	52.5	24.1	14.7	6.2	
	53 000	2.7	50.4	24.1	15.2	7.1	
	BWR*	27 500	2.6	59.8	23.7	10.6	3.3
		30 400	N/A**	56.8	23.8	14.3	5.1
HWR	7 500	–	66.6	26.6	5.3	1.5	
GCR	3 000	0.1	80.0	16.9	2.7	0.3	
	5 000	N/A**	68.5	25.0	5.3	1.2	
AGR	18 000	0.6	53.7	30.8	9.9	5.0	
LWGR	18 500	N/A**	≈49	≈35	≈10	≈6	
Weapons-grade plutonium (WGPu)	≈1 000	–	93.5	6	0.5	–	

* PWR = Pressurized water reactor, BWR = Boiling water reactor

** N/A = Not available

Table 5.3. Isotopic composition of spent fuel from civil nuclear power reactors for

¹⁶. The burn-up of spent fuel is usually given as the number of days the fuel has been used in the reactor times the thermal capacity of the reactor divided by the mass of the uranium in the fuel. A common unit is MW_{th}·days·(kgU)⁻¹. See also Section 2.3.

normal burn-up¹⁷

The reason for bringing up this subject is that we will concentrate the discussion of the results of this scenario to the plutonium produced in the most common reactor, the light-water reactor. This will simplify the discussion in Chapter 6 somewhat with respect to the long-term military potential of RGPu. This means that in the following discussion the term "RGPu" is used as a term for all the types of plutonium produced in the above civil nuclear reactors, with the composition defined as that given in the first row of table 5.3, i.e., to that of a light-water PWR fuelled with 3.25% enriched uranium to a burn-up of 33 000 MW_{th}·days·(kgU)⁻¹, immediately after unloading from the reactor¹⁸. This type of plutonium will be the most abundant type of plutonium to dispose of in a future post-nuclear world. At this stage we will only point out that the main difference from the other types of RGPu is that:

- in the reactors that are fuelled with natural uranium (the HWR and GCR reactors) the ²³⁵U content in the fuel is lower. This means that the production of ²³⁸Pu is lower (see figure 2.9).
- these reactors normally have a lower burn-up of the fuel than the light-water reactors. This means that the relative content of the isotopes ²³⁹Pu and ²⁴¹Pu (the fissile fraction) is higher than in plutonium from light-water reactors, as shown in table 5.4.
- the AGR and HWGR reactors have a lower fissile fraction in the plutonium than does LWR plutonium.

Reactor type	Fissile component [%]	Even-isotope component [%]
LWR	70.4	29.6
HWR	71.9	28.1
GCR	78.3	21.7
AGR	63.6	36.4
LWGR	≈59	≈41
WGPu	94	6

Table 5.4. Fissile and even-isotope components of different types of RGPu¹⁹

¹⁷. Sources: OECD/NEA (1989, pp. 23, 30) & Farmer (1983, p. 17), except for the light-water graphite reactors which is from Klimov (1975, p. 383) and Chantoin (1992).

¹⁸. This is identical to the definition made in Chapter 2.

¹⁹. From table 5.3 at a "normal" burn-up of 33 000 MW_{th}·days·(kgU)⁻¹ for the light-water reactor (PWR), 7 500 MW_{th}·days·(kgU)⁻¹ for the heavy-water reactor (PWR), 4 000 MW_{th}·days·(kgU)⁻¹ for the gas-cooled reactor (GCR), 18 000 MW_{th}·days·(kgU)⁻¹ for the AGR and 18 500 MW_{th}·days·(kgU)⁻¹ for the light-water graphite reactor (LWGR).

Because the fissile component, and especially the ^{239}Pu content, of some types of non-light-water reactor plutonium is higher than that of light-water reactors, the use of such plutonium for the construction of nuclear explosives is comparatively easier. In the discussion in Chapter 6 of the possibilities of using RGPu for the construction of nuclear devices, we will therefore sometimes underestimate the quality of the plutonium for this purpose²⁰.

In order to make an estimate of the total amount of plutonium produced in the scenario, we need a figure for the amount of plutonium produced per year in a civil nuclear reactor. This figure is dependent on several factors. Naturally, it is dependent on the size and capacity of the reactor, but it is also related to the type of reactor and to the load factor of the reactor, i.e., for how many days in the year the reactor has been running²¹.

Table 5.5 gives some values for the production of plutonium in the different types of civil nuclear power reactors. These values are given as $\text{kg}\cdot(\text{GW}_e)^{-1}\cdot\text{year}^{-1}$.

Reactor type	Plutonium production [$\text{kg}\cdot(\text{GW}_e)^{-1}\cdot\text{year}^{-1}$]
LWR	331
HWR	662
GCR	852
AGR	217
LWGR	234

Table 5.5. Production of plutonium in civil nuclear power reactors²²

As can be seen, the gas-cooled reactor and the heavy-water reactor produce more plutonium per $\text{GW}_e\cdot\text{year}$ than does the light-water reactor.

In order to obtain an estimate of the actual production one also has to take into account the load factor of the reactors. Recent IAEA data for cumulative load factors

²⁰. We can here repeat the observation from Chapter 2 that there is a distribution of the quality of plutonium in a core, and that some fuel rods may have been removed with a very low burn-up if the rod is, for example, damaged.

It is also worth noting that some experimental work has been carried out on operating nuclear reactors to higher burn-up by using uranium fuel with higher enrichment. Plutonium from such fuel would have a lower fissile component.

²¹. The load factor (LF) expressed in percent is defined as (IAEA 1991A, p. 6):

$$\text{LF}(\%) = \frac{E_{\text{net}}}{E_{\text{max}}} \quad \text{where}$$

E_{net} = Net electrical energy ($\text{MW}_e\cdot\text{hours}$) produced during the reference period under consideration

E_{max} = Net electrical energy ($\text{MW}_e\cdot\text{hours}$) which would have been produced at maximum net capacity under continuous operation during the whole of the reference period

²². These values are calculated using data from table 5.4 and from OECD/NEA (1989, table 10, p. 42), except for the LWGR which is from Chantoin (1992).

for non-prototype civil power reactors in the world up to and including 1989 are reproduced in table 5.6. The data give an average load factor of 66.8% (IAEA 1991A, p. 48). An average of all types of light-water reactors gives a value of 67.2%.

It would be possible to use only data for the light-water reactors in a calculation of the total plutonium amounts produced in the scenario. For example, if one uses a load factor of 67% and a value of total plutonium production of 233 kg·(GW_e)⁻¹·year⁻¹, one arrives at a value of RGPu production for light-water reactors of 156 kg·(GW_e)⁻¹·year⁻¹.

In the following calculations, however, we will use the load factors and plutonium production values shown in table 5.7.

Reactor type		Average load factors [%]
LWR	PWR (<600 MW _e)	74.8
	PWR (≥600 MW _e)	66.4
	BWR (<600 MW _e)	64.9
	BWR (≥600 MW _e)	62.6
HWR	(<600 MW _e)	66.5
	(≥600 MW _e)	79.8
GCR		66.9
AGR		61.8
LWGR		72.3

Table 5.6. Nuclear power reactor load factors²³

Reactor type	Plutonium production [kg·(GW _e) ⁻¹ ·year ⁻¹]	Load factor [%]
LWR	331	67
HWR	662	75
GCR	852	67
AGR	217	62
LWGR	234	72

Table 5.7. Plutonium production and reactor load factors used in our scenario

Figure 5.7 shows the annual global plutonium production of RGPu in civil nuclear power reactors in the scenario using the data base described above and the values in table 5.7.

²³. Source: IAEA (1991A, p. 48).

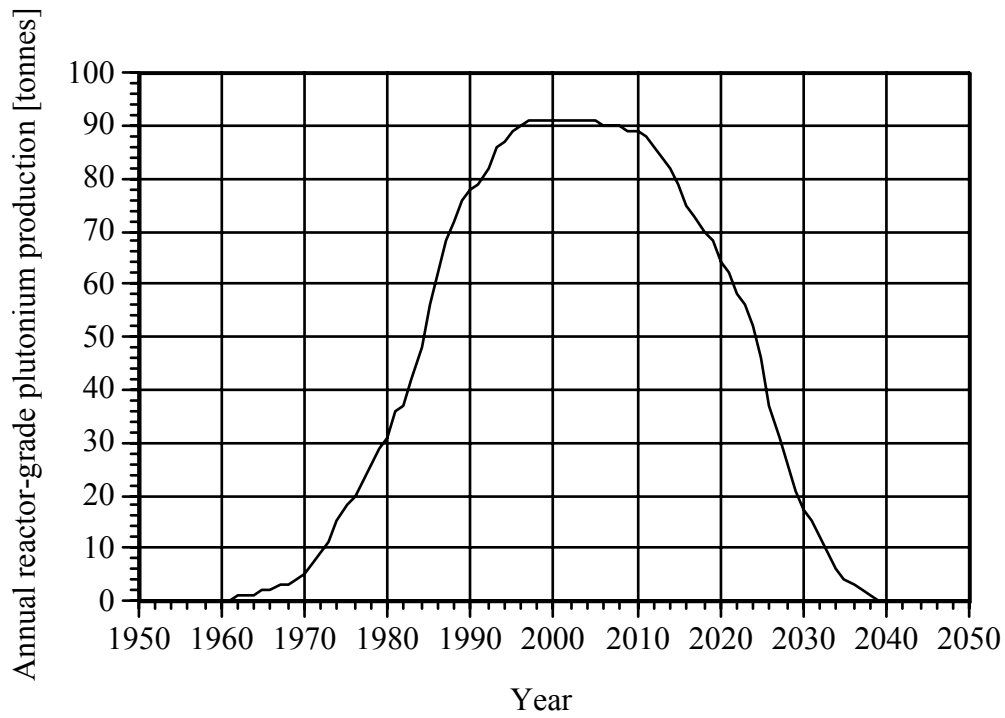


Figure 5.7. The global annual production of RGPu in civil nuclear power reactors

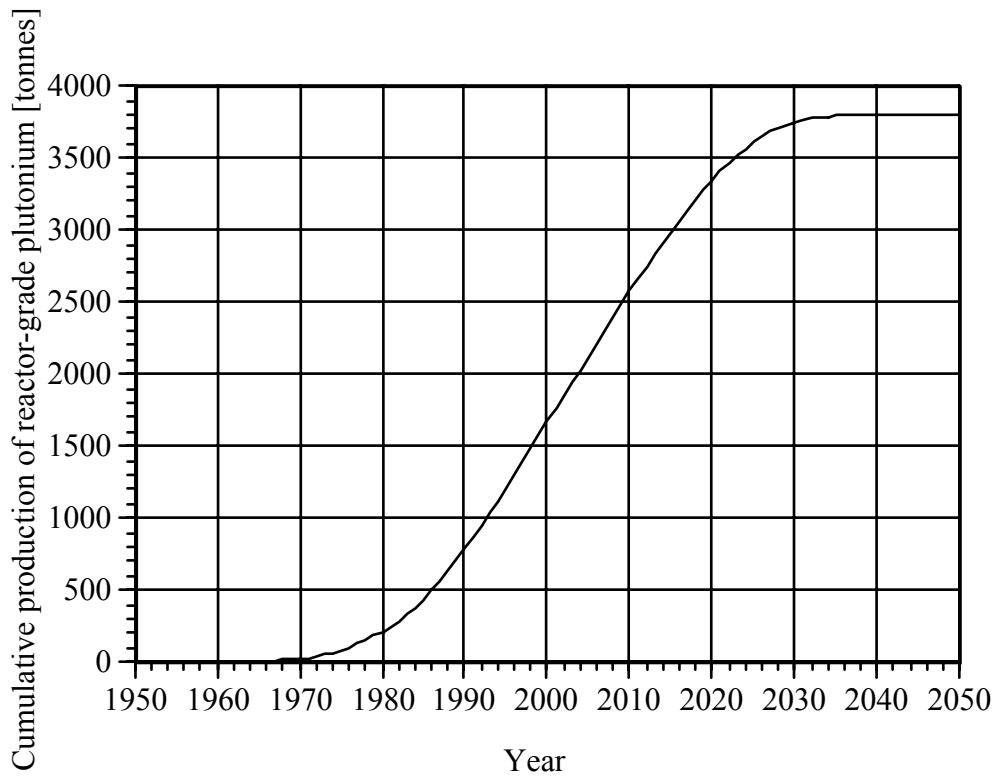


Figure 5.8. Total cumulative production of RGPu in civil nuclear power reactors in the scenario

As can be seen in the figure the annual global production is at present approximately 80 tonnes of plutonium per year. The annual production in the scenario follows the curve in figure 5.2 and peaks around the year 2000 at a yearly production of a little over 90 tonnes.

Figure 5.8 shows the cumulative global production of RGPu in civil nuclear power reactors in the scenario.

We can see that the scenario gives a cumulative amount of about 870 tonnes of plutonium produced through 1990. The total amount of RGPu produced in the worlds civil nuclear power reactors until the shutdown of the last reactor in 2039 is 3 795 tonnes.

Here we have not discussed the world's civil research reactors. There are two main reasons for this. Firstly, there are comparatively small amounts of plutonium produced in these reactors, as they are fuelled with highly-enriched uranium. Secondly there is relatively little plutonium produced because they are of much smaller capacity.

Finally a short word about the dependency of the plutonium production figure on the choice of mean lifetime for the reactors. Although no exact calculations have been carried out, these values would lie approximately at the same relative levels as those presented for the accumulated nuclear generation capacity in figure 5.6, i.e., would represent approximately 2 370 tonnes for a 25 year lifetime, 2 840 tonnes for a 30 year lifetime and 3 320 tonnes for a 35 year lifetime.

5.2.2 *Amounts of Reprocessed Reactor-grade Plutonium*²⁴

In table 5.8 is shown the cumulative separation of RGPu in reprocessing plants in the world through 1990. As we can see, approximately 125 tonnes of RGPu has been separated. If the set up plans for reprocessing continue to be followed this amount might increase to 340 tonnes by the year 2000 and 650 tonnes by the year 2010. In the scenario above we have estimated that nearly 790 tonnes of RGPu had been produced by the year 1990²⁶. 125 tonnes would represent 16% of this amount.

Only minor parts of the separated RGPu has been recycled. The present total MOX-fuel fabrication capacity can use approximately 4.3 tonnes of plutonium per year and there is practically no use of RGPu as FBR-fuel. The total amount of plutonium being recovered in reprocessing is between 10 and 15 tonnes per year (Albright and Feiveson 1992, p. 80, IAEA 1991B, pp. C30-C31)²⁷. There is thus a reprocessing overcapacity for RGPu compared to the MOX-fuel fabrication facilities and the already large stocks of separated plutonium are growing. As indicated briefly in Chapter 4, there are, however, problems ahead, in at least Europe, that may halt the reprocessing and recycling of RGPu in the not too distant future.

²⁴ This section is based on Albright (1991).

²⁵ This section is based on Albright (1991).

²⁶ Albright (1991) estimates the total RGPu discharged in civil spent nuclear power fuel to be 650 tonnes through 1990, i.e., a little lower than in our scenario.

²⁷ In the scenario we found that the present production of new RGPu in spent fuel is 55 tonnes per year.

Country	Reprocessed amounts [tonnes]
Belgium	0.7
France	43.8
Germany	1.1
Japan	3.4
United States	1.4
United Kingdom	50.3
Soviet Union (former)	~ 25
India	~ 0.75 (?)
Total (rounded off)	125

Table 5.8. Civilian separation of RGPu through 1990²⁸

5.3 The Production of Weapons-grade Uranium and Weapons-grade Plutonium in Military Nuclear Programmes

In this scenario we have stipulated that there are two developments within the global military programmes.

- The production of new fissile material for the nuclear weapons arsenals is discontinued²⁹ and the nuclear arsenals of the world are gradually reduced to very low levels.
- The use of highly-enriched or medium-enriched uranium in military naval propulsion and space-based reactors, as well as in civil nuclear research reactors, is slowly phased out.

The first of these developments has in practice already started. With the cut-back of the super-powers' nuclear arsenals, the demand for the production of new WGPu is non-existent. Both the INF and START treaties allow the recycling of the fissile material in the nuclear warheads of the removed nuclear weapons.

In addition, the production of weapons-grade (highly-enriched) uranium was discontinued in the United States in 1964, because the stockpiles of the material were so large, and the production of WGPu in the United States was halted in the late 1980's because of concern for the lack of safety of the military plutonium-producing reactors. In the former Soviet Union 7 of the 13 WGPu production reactors have been shut down. The remaining reactors, near Tomsk and Krasnoyarsk, are committed to be shut down before the year 2000³⁰. Apparently these reactors also supply district heat and electricity to the surrounding communities. With the

²⁸. From Albright (1991). The question mark for India is in the original.

²⁹. Several proposals for a ban on the production of military fissile material have been made. See, for example, von Hippel, Albright & Levi (1985), von Hippel & Levi (1985)

³⁰. von Hippel (1991).

continuing cuts in the nuclear arsenals it is unlikely that these production facilities will be restarted, and other nuclear weapon states could follow suit³¹.

The global reductions of nuclear weapon arsenals are starting. Although only the superpowers have actually begun cutting down the arsenals, other nuclear weapons states can be expected to follow. A result of this is that there will be large amounts of WGPu and WGU to dispose of as high-level waste.

The second of these developments is less certain in the short-term, but towards the end of the scenario, in the middle of the next century, there is a high likelihood that they will have been fulfilled.

In the following we estimate, as part of the scenario, the total amounts of WGU and WGPu that have been produced in the world.

5.3.1 *Weapons-grade Plutonium*

Some attempts have been made to estimate the quantity of weapons-grade plutonium (WGPu) in the global nuclear weapons stockpiles. Great efforts and complex methodology have been used in order to calculate these amounts from the relatively scarce information that exists about the military nuclear programmes of the nuclear weapon states, especially from the Soviet Union, and China³². For this scenario the exact figures are not decisive for the continuing discussion and the figures given below are to be taken only as rough estimates³³.

Table 5.9. lists an estimate of the amounts of WGPu in the stockpiles of the world's nuclear weapon states. Of the emerging nuclear states only India and Israel can have produced larger amounts of WGPu, but these are still negligible in the total amount³⁴.

The total amount of the world's stocks of WGPu in the scenario is therefore estimated to be 233 tonnes³⁵.

³¹. Presently the main discussion about the future of the United States military nuclear material production reactors concern the production of tritium. This isotope which, as was explained in Chapter 3, is used for the construction of fusion-boosted fission and fusion nuclear warheads. As tritium has a relatively short half-life of 12.3 years, it needs to be replaced at intervals. Possible alternatives in the case of the United States seem to be to refurbish and restart an old military reactor, to build a new reactor or to produce the tritium in an accelerator based production system. As there are considerable amounts of tritium to be recycled from the present cuts in the nuclear arsenal, the decision of which way to proceed has not been taken so far.

³². See, for example, von Hippel, Albright & Levi (1986).

³³. We have here used the amounts given by Albright (1991). Similar estimates, and a background to how such estimates can be made, can be found in von Hippel, Albright & Levi (1986), Cochran et al. (1987A), Cochran et al. (1987B), Cochran et al. (1989).

³⁴. If Israel has as many as 100 nuclear warheads, as is sometimes suggested, the WGPu in these could be approximately 0.5 tonnes.

³⁵. There is also some fuel-grade plutonium that have produced in the military nuclear material production reactors. Albright (1991) estimates these amounts to be 8 tonnes for the United States and 15 tonnes for the former Soviet Union.

Country	Amounts [tonnes]
United States	97 ± 8
Soviet Union (former)	125 ± 25
United Kingdom	3.7
France	5 ± 1.6
China	2.5 ± 1.5
Other countries	negligible
Total	233 ± 36

Table 5.9. An estimate of the global amounts of WGPu

5.3.2 *Weapons-grade Uranium*

The other fissile material in the nuclear warheads in the world’s nuclear arsenals is weapons-grade uranium (WGU). Table 5.10 shows an estimate of the amounts of WGU that exists in today’s global stockpiles³⁶. No estimate has been made for the minor nuclear powers³⁷ or for the emerging nuclear states³⁸.

Country	Amounts [tonnes]
United States	600
Soviet Union (former)	500
United Kingdom, France, China	not available
Other countries	negligible
Total	1100

Table 5.10. An estimate of global amounts of WGU

The total that is used in this scenario is estimated to be 1100 tonnes. This figure is relatively uncertain, but fortunately it is not of such great importance in the

³⁶. We have here used as sources von Hippel, Albright & Levi (1986), Cochran et al. (1987A), Cochran et al. (1987B), Cochran et al. (1989).

The estimate for the former Soviet Union has a large uncertainty, maybe as much as ±250 (von Hippel, Albright & Levi, p. 2-18).

³⁷. The United States supplied the United Kingdom, and to a certain extent France, with WGU for military purposes, i.e., primarily for use in naval reactors (von Hippel et al. 1986, p. 2-8). France has a uranium enrichment plant of its own at Pierrelatte (Davies 1988, p. 67). Most of the highly-enriched uranium produced at this plant has probably been used in the country's military naval reactors.

³⁸. Pakistan and perhaps South Africa could have produced small amounts of WGU for military explosive purposes.

continued discussion³⁹.

5.4 A Comparison With Other Scenarios

How does this scenario compare with other scenarios that discuss the future of civilian nuclear power? Conventional scenarios developed by organizations that have interests in an expansion of nuclear power all base their scenarios on two basic assumptions⁴⁰:

- Economic growth will continue and with it will follow a growth in the use of energy, in particular electricity.
- At least part of this growth will be covered by nuclear power.

This type of scenarios have been developed by, for example, the International Atomic Energy Agency alone (IAEA 1991E)⁴¹, and the United States Department of Energy (United States DOE 1990).

Scenario	Nuclear power generating capacity [GW _e]			
	1990	2000	2005	2010
Our	329	383	382	376
IAEA (low)	325.9	387	420	456
IAEA (high)	325.9	406	467	577

Table 5.11. Estimates of global nuclear generating capacity

In table 5.11 and figure 5.9 we compare our scenario with a high and a low scenario presented in IAEA (1991E, p. 16). As can be seen they are very similar until a few years into the next century when IAEA expects the total global nuclear electricity generation to start to increase again.

Another, similar, comparison can be made with projections that the United States Department of Energy’s Energy Information Administration has made for future United States nuclear generation capacity (United States DOE 1990, p. 13). They also present a high (upper) and a low scenario as well as a “no new orders” scenario that is very similar to the one developed in this thesis. The scenarios are compared in table 5.12 and figure 5.10.

³⁹. Relatively large amounts of HEU/WGU has also been produced for the use in naval propulsion reactors. These amounts are however consumed as the reactors are operating. If the fuel in the reactors is reprocessed, no WGU is left to be disposed of in burnt out cores.

⁴⁰. In addition, in later years, scenarios have been constructed in which nuclear power will be used to hinder the development of greenhouse warming due to fossil-fuel burning. A scenarios of this type is discussed below.

⁴¹. A similar scenario is constructed in OECD/NEA/IAEA (1987).

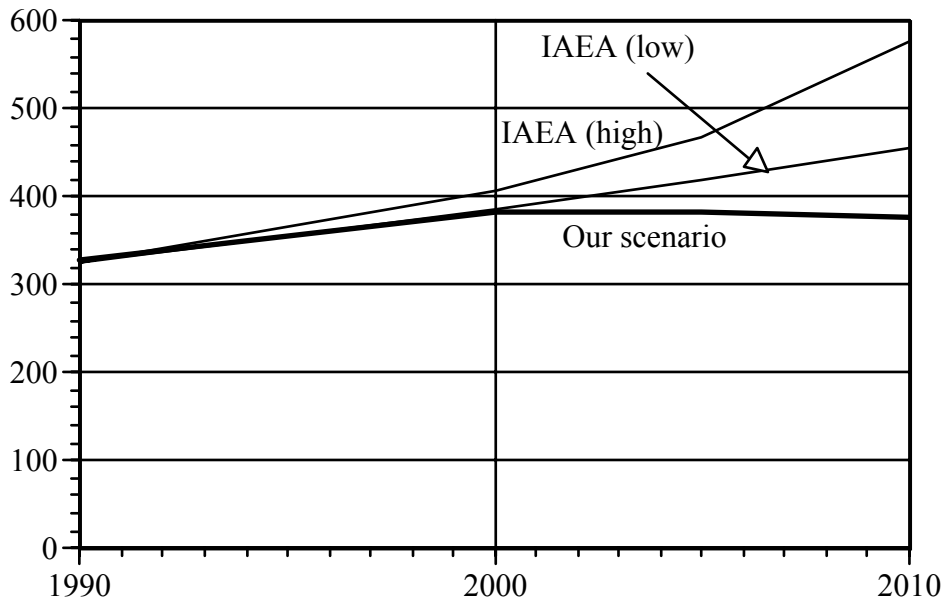


Figure 5.9. Estimates of global nuclear generating capacity

Scenario	Nuclear power generating capacity [GW _e]									
	1990	1995	2000	2005	2010	2015	2020	2025	2030	
Our	101	102	102	102	98	66	53	29	1	
DOE (upper)	99	103	104	105	122	124	146	165	184	
DOE (lower)	99	103	104	105	103	103	116	125	134	
DOE (no new orders)	99	103	104	104	100	69	54	28	6	

Table 5.12. Estimates of United States nuclear generating capacity

As we can see, the upper and lower DOE scenarios lead, like the IAEA scenarios, upwards in the beginning of the next century. The lower scenario reflects a “slower anticipated start-up of the nuclear industry and a slower rate of new plant orders” (United States DOE 1990, p. 12). We can also see that, not surprisingly, the “no new orders” scenario (thinner line) follows our scenario quite closely and is only visible at all as a small deviation at a few places.

An important question is whether the scenario is stable, and whether the eventual inaccuracies in the scenario will strongly affect the analysis, later in this thesis, that uses the scenario. We answer this question by first splitting the question into two parts:

- Will minor changes in the assumptions or recent changes that concern the

- development of civil nuclear power affect the stability of the scenario?
- Will inaccuracies in the predictability of the scenario affect the analysis that follows in the following sections?

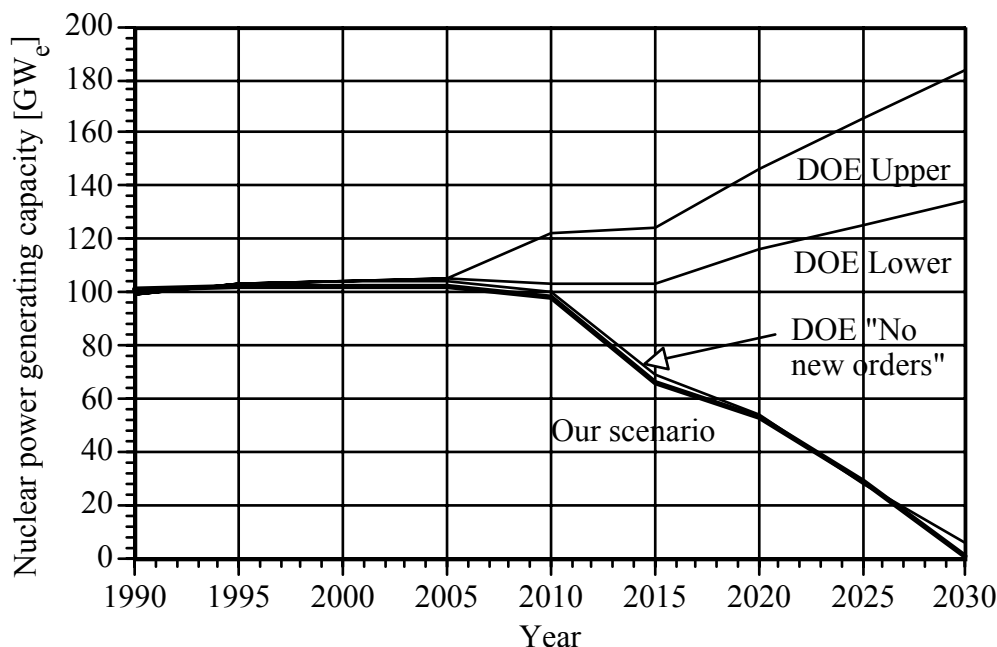


Figure 5.10. Estimates of United States nuclear generating capacity

The answer to the first question seems to be no. Data from 1990 are used for the development of the scenario. Minor changes, such as a few new orders for reactors or a few reactors shut down before a lifetime of forty years change the results of the result of scenario only marginally. The uncertainties that are built into the scenario due to, for example, changes in choice of lifetime or availability, are relatively large compared to a few orders for new reactors in France, Canada, Japan, South Korea, China, India or Finland. In this context the scenario is thus relatively immune to small changes.

To answer the second question we can ask ourselves what would happen if there is a renaissance for nuclear power and a new generation of nuclear power reactors are constructed and operated. Let us first assume that they become the last nuclear power plants that are operated and a new scenario could be constructed for the production of RGPu to remain to be disposed of in a post-nuclear world after they were shut down. Then, our scenario is a lower limit to this second scenario. The long-term nuclear explosives predicament examined in the next chapter will, however, still exist because there will be a post-nuclear world.

What happens if the expansion of nuclear power just continues. We have stated in the introductory chapter that this would lead to a plutonium economy and that there would then be practically no fissile material that would be have to be disposed of. There is therefore no predicament. Or, would there? After all, there would be large amounts of WGPu constantly circulating in such a society, as the plutonium

economy would in the long run have to rely on FBRs recycling WGPu.

How would we approach a plutonium economy? Let us study a scenario developed by Wolf Häfele (1990A, 1990B). Häfele considers the greenhouse effect to be a powerful argument for increasing use of nuclear power, if safety and waste problems can be overcome. He then finds that the safety of the present generation of nuclear power reactors is insufficient and that they imply unacceptable risks. Therefore, the increased use of nuclear power has to be carried out using new reactors that are “inherently safe”. He assumes that such reactors can be made safe enough for a long-term nuclear future. Light-water reactors of this type are on the drawing table. Häfele then wants to expand nuclear power to a 2 000 GW_e electricity generating capacity by the year 2030⁴². 40 GW_e would have to be added each year, representing forty 1 000 MW_e nuclear reactors.

How would these reactors be fuelled? Häfele finds that the 2 000 GW_e nuclear electricity generating capacity would exhaust the known global uranium supply in 20 years, only half-way into the scenario. The solution is then to start using fast breeder reactors in a plutonium economy⁴³.

5.5 Summary of Amounts Militarily Usable Fissile Material in the Scenario

Table 5.13 is a summary of the amounts of the total global amounts of militarily usable fissile material that is produced during the time-scale that the scenario covers. This is the material that is left to be dealt with by future generations living in the post-nuclear era assumed to begin in the middle of the next century. In the next chapter we will explore the long-term nuclear explosives predicament that they might have to face.

Material	Amounts [tonnes]
RGPu	3 795
WGPu	233
WGU	1 100

Table 5.13. Total amounts of militarily usable fissile material produced in the scenario

⁴². This can be compared to our scenario where nuclear power electricity generating capacity will peak at below 400 GW_e.

⁴³. Häfele seems to miss the implications of this. He starts off by implying that nuclear power is not safe enough and wants to change the next generation of nuclear reactors to a safer type. He ends up by stating that within 20 years time we have to use fast breeder reactors, a technology where the development of inherently safe systems may be difficult.

6. LONG-TERM NUCLEAR EXPLOSIVES POTENTIAL OF MILITARILY USABLE FISSILE MATERIAL

In the previous chapter we have developed a scenario for the amounts of militarily usable fissile materials that will be produced until the middle of the next century and that will be left to dispose of as nuclear waste in a possible “post-nuclear world”. In this chapter we will examine one characteristic of this waste, the ability to use the fissile material in it for the construction of new nuclear weapons. We will show special interest in the long-term characteristics of the fissile material in this regard. By long-term we here mean up to 1 million years into the future.

Studies of the long-term characteristics of civil high-level nuclear reactor waste have very much been dominated by the environmental effects of the waste. Figures, such as figure 4.1, show that the activity in the spent direct disposal nuclear waste makes the waste a very long-term environmental hazard.

The long-term explosives potential of the fissile material in the high-level nuclear waste has not been widely studied¹. We found that in our scenario we have approximately 3 795 tonnes of reactor-grade plutonium (RGPu), 233 tonnes of weapons-grade plutonium (WGPu) and 1 100 tonnes of weapons-grade uranium (WGU) that may remain to be disposed of as high-level nuclear waste in a post-nuclear world.

Technology level	Weapons-grade plutonium [kg]	Weapons-grade uranium [kg]	Reactor-grade plutonium [kg]
Manhattan project	6	60	–
Present-day technology	3	20	4

Table 6.1. Estimates of the amounts of fissile material necessary for the construction of nuclear explosives

Table 6.1 shows conservative estimates, based on the discussion in Chapter 3, of the amounts of fissionable material of different qualities that are necessary in order to construct a nuclear explosive. We have given values both for a technology level for nuclear explosives construction that was used in the Manhattan project and for a

¹. This problem, that we in this thesis called the long-term nuclear explosives predicament, has been largely neglected in the discussions of the direct disposal of spent civil high-level waste from nuclear power reactors. The reasons for this and possible solutions are discussed in the following chapters. There was an attempt to put this issue on the agenda in Sweden in the mid-1980's. In 1985, Professor Lars Nordström, who had previously been Director-General of the Swedish Nuclear Power Inspectorate, introduced the idea that the final repositories for spent fuel might in the long run become plutonium “mines” (Dagens Nyheter 1985A). This possibility was at this time rejected as faulty or irrelevant by the nuclear industry, but was examined within some authorities. See, for example, SKB (1985), Dagens Nyheter (1985B), SKI (1986), Strömberg (1986), and KASAM (1987, pp. 128-9).

level available to a present-day industrial country².

These figures imply that if our scenario holds true there will be militarily usable fissile material that could be used to construct over 1 million nuclear explosives, using present-day technology, in the world by the year 2040. The numbers for each type of fissile material are shown in table 6.2. Using only the RGPu in the scenario one could construct about 950 000 nuclear explosives. This alone is over 16 times the number of nuclear warheads that were present in the world's nuclear arsenals before reductions were started in 1988-89³.

Type of fissionable material	Amounts [tonnes]	Number of nuclear explosives that can constructed using present-day technology
Reactor-grade plutonium	3 795	950 000
Weapons-grade plutonium	233	78 000
Weapons-grade uranium	1 100	55 000
Total	5 128	1 083 000

Table 6.2. Number of nuclear explosives that can be constructed using the fissile material in the scenario

After a short discussion of how the isotope composition changes over time we will show how these number decreases with time. But first, we are interested in the long-term characteristics for the construction of nuclear explosives of the fissile material. When it comes to the fissile material which is already of weapons-grade quality, i.e., the WGPu and WGU that are already separated, there is not so much that needs to be discussed. The WGU contains the isotopes ²³⁵U and ²³⁸U, both which have very long half-lives⁴. The amounts and characteristics of this material therefore change very little even in the time-scale we are discussing here. The WGPu does change somewhat with time, both with regards to amounts and, somewhat of less importance, to composition. We will bring this question up where relevant.

The result of this discussion is that it is the RGPu that concerns us the most. In Chapter 3 the possibilities of using RGPu for the construction of nuclear explosives were demonstrated. Because of the different half-lives of the different plutonium isotopes in the plutonium, some of the characteristics that are important for

². The Fat Man nuclear bomb that was exploded over Nagasaki reportedly used 6.2 kg of WGPu and the Little Boy nuclear bomb that as exploded over Hiroshima reportedly used 60 kg of WGU, albeit at an enrichment level of only 80% (Hansen, 1988, p. 21).

³. In 1988, the United States had approximately 23 400, the Soviet Union approximately 33 000, the United Kingdom approximately 330, France approximately 500 and China approximately 350 nuclear warheads (Nuclear Notebook 1989, SIPRI 1989), making a total of 57 600 warheads.

⁴. The half-life for ²³⁵U is 7.04·10⁸ years and for ²³⁸U is 4.47·10⁹ years. Data are from table 2.3.

explosives construction change over time. In addition, if the RGPu is residing in unreprocessed directly disposed spent nuclear fuel the ease of removing the plutonium from the rest of the high-level nuclear waste also changes. A third aspect that changes over time is the possibility of isotope separation of the plutonium.

In the rest of this section, an analysis is made of the consequences of these changes, for both relatively short-term time-scales, i.e., up to approximately a thousand years from now, and also for the long-term time-scale, i.e., up to 1 million years from now, that the spent high-level nuclear waste will also be an environmental hazard.

6.1 Changes in Plutonium Isotope Composition

The different half-lives of the plutonium isotopes are given in table 6.3. Because of these differences in half-life the different plutonium isotopes decay at different rates and the relative amounts of the isotope remaining after a certain number of years varies.

Isotope	Half-life [years]
^{238}Pu	87.7
^{239}Pu	24 100
^{240}Pu	6 540
^{241}Pu	14.4
^{242}Pu	376 000

Table 6.3. The half-lives of the different plutonium isotopes⁵

In this section we are going to study how the plutonium composition of RGPu and WGPu change over time as well as try to give an estimate of how many nuclear explosives the fissile material in the scenario can be used for into the long-term future.

6.1.1 Reactor-grade Plutonium

In figure 6.1a the amounts of the different plutonium isotopes of RGPu that remain after a certain time are plotted from one year from the removal from the reactor up to 1 million years into the future. Figure 6.1b shows the same data in a linear scale from 0 to 50 000 years.

⁵. Data are from table 2.3.

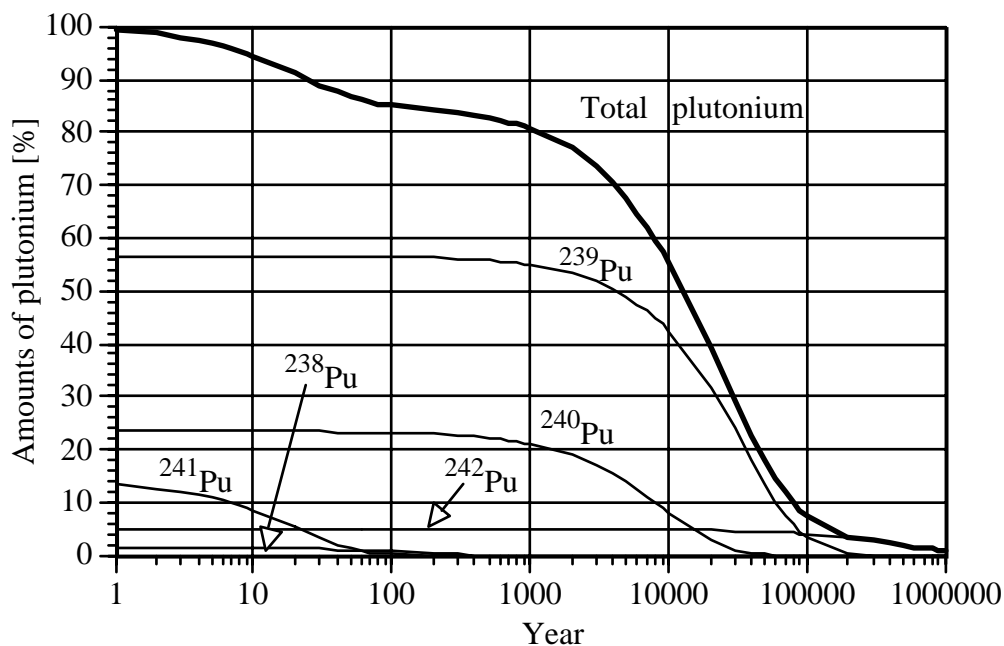


Figure 6.1a. Amounts of reactor-grade plutonium (Total plutonium is in percent of original amount of plutonium, individual isotopes can be seen in relation to their proportional isotope composition at year 1)

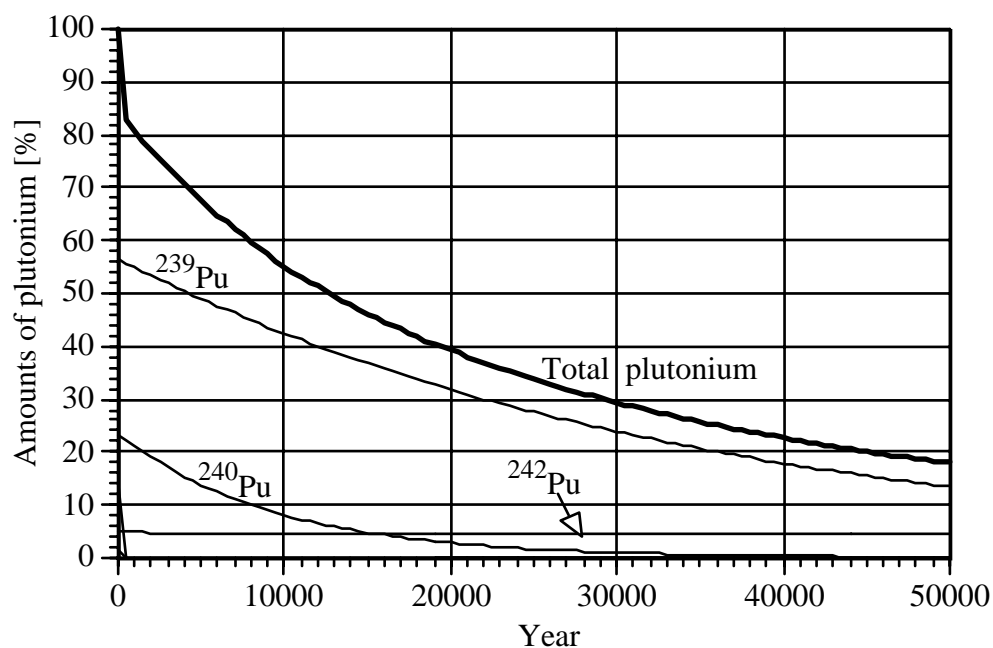


Figure 6.1b. Amounts of reactor-grade plutonium (Total plutonium is in percent of original plutonium, individual isotopes can be seen in relation to their levels at year 0)

We can see some interesting features in the figures. The total plutonium content decreases only slowly for the first 100 years to approximately 90% and to approximately 80% in 1000 years. At 10 000 years we come down to about 60% and after 100 000 years we have reached a level of 10%. The plutonium isotopes ^{241}Pu and ^{238}Pu decay away first. After 150 years the ^{241}Pu is essentially gone⁶. After 1 000 years the same is the case for the ^{238}Pu and after 70 000 years for ^{240}Pu . After about 250 000 years when the decay of ^{239}Pu has advanced to low amounts, all that remains is essentially ^{242}Pu .

It is not only the quantitative amounts of plutonium that are of interest. The relative amounts of the plutonium isotopes in the plutonium are important when discussing the characteristics for weapons construction. Figure 6.2a and 6.2b shows how the relative isotope composition changes with time.

We can see that the relative amount of ^{239}Pu increases for the first 20 000 years, as first the ^{241}Pu , then the ^{238}Pu and finally the ^{240}Pu decays away. The relative ^{239}Pu content then starts to decrease and after about 75 000 years it is the ^{242}Pu that dominates.

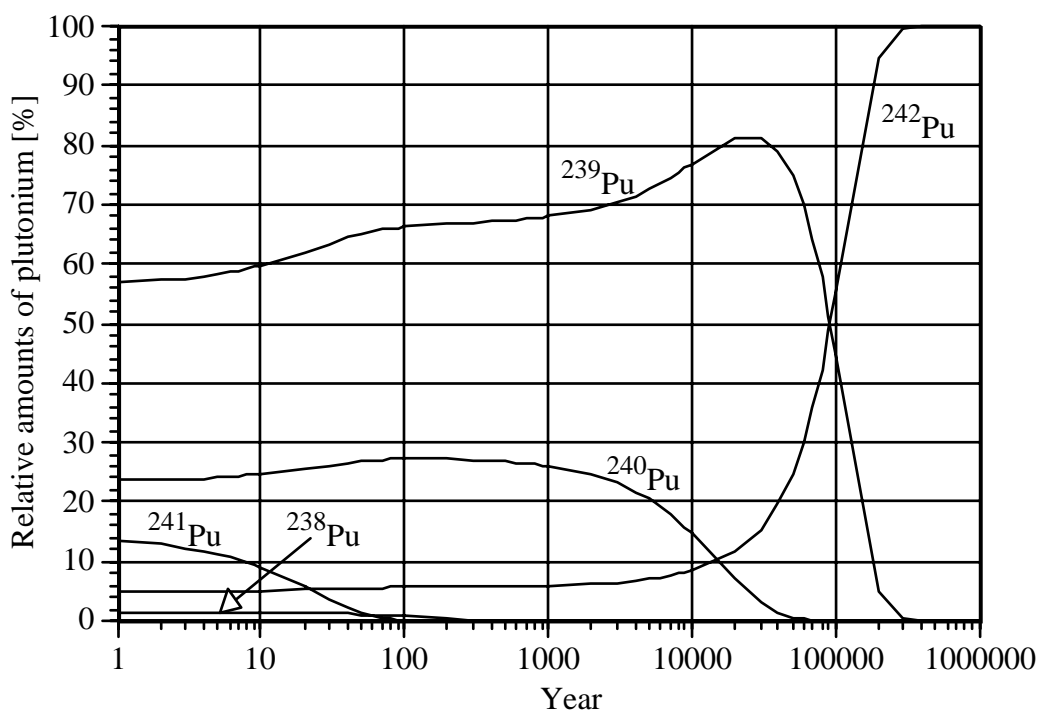


Figure 6.2a. Relative composition of plutonium isotopes in reactor-grade plutonium

⁶. As a rule of thumb, an isotope has decayed away in about 10 half-lives. After this time only 1/1000 of the original amount remains. After 20 half-lives 1/1 000 000 of the original amount remains.

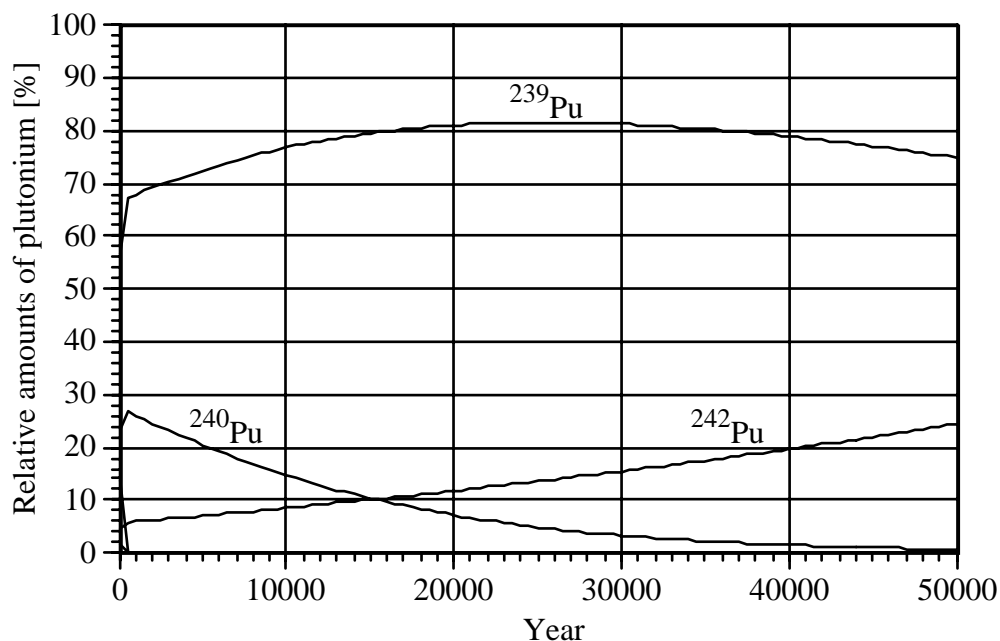


Figure 6.2b. Relative composition of plutonium isotopes in reactor-grade plutonium

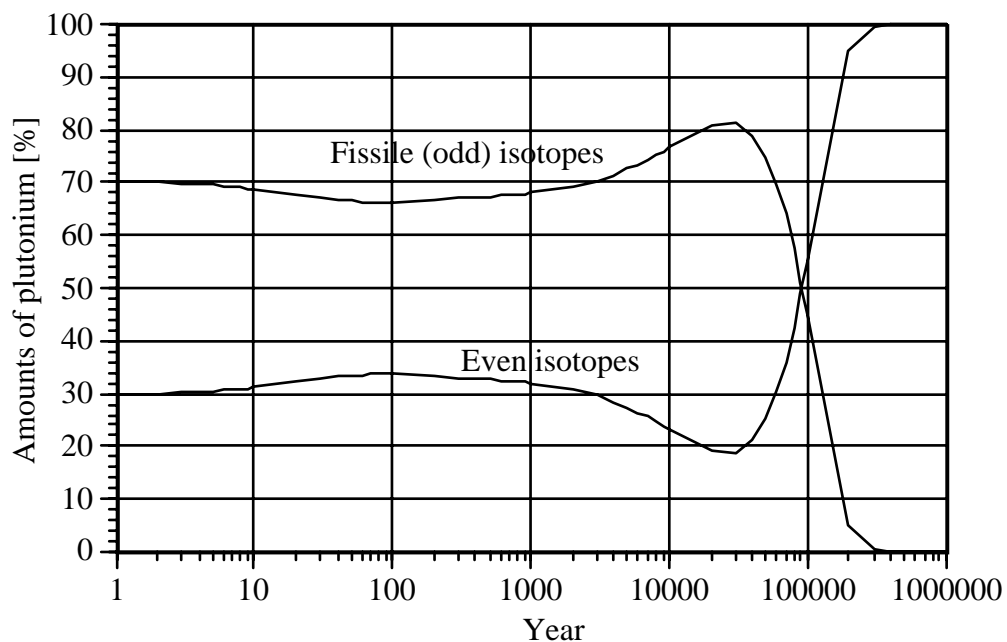


Figure 6.3. Relative isotope composition of fissile and even isotope components of reactor-grade plutonium

It is also interesting to study the fissile (odd-isotope) versus the even-isotope composition of the RGPu. The relative isotope composition of these are plotted in figures 6.3. One can see that the relation between the two components is relatively stable for a long period of time. If a rough estimate is to be taken for how long the RGPu is useful for the construction of nuclear explosives one can ask for how long this relationship holds and one finds that after approximately 70 000 years the fissile component has fallen 10% below its original value and only declines further. This is

a good rough estimate of the time that the RGPu is directly usable for the construction of nuclear explosives, as discussed in Chapter 3, without any isotope separation⁷.

6.1.2 Weapons-grade Plutonium

Figures 6.4a and 6.4b shows the plutonium amounts as well as relative composition of WGPu with time. We can see that 90% of the plutonium that remain after 3 000 years, 50% of the plutonium remains after approximately 20 000 years, 10% of the plutonium remains after approximately 80 000 years and that not until over 250 000 years into the future the amounts of WGPu decrease to relatively low levels. As the half-life of ^{240}Pu is shorter than that of ^{239}Pu , the WGPu becomes almost pure plutonium-239 as the years pass and it becomes so-called super-grade plutonium after approximately 25 000 years⁸.

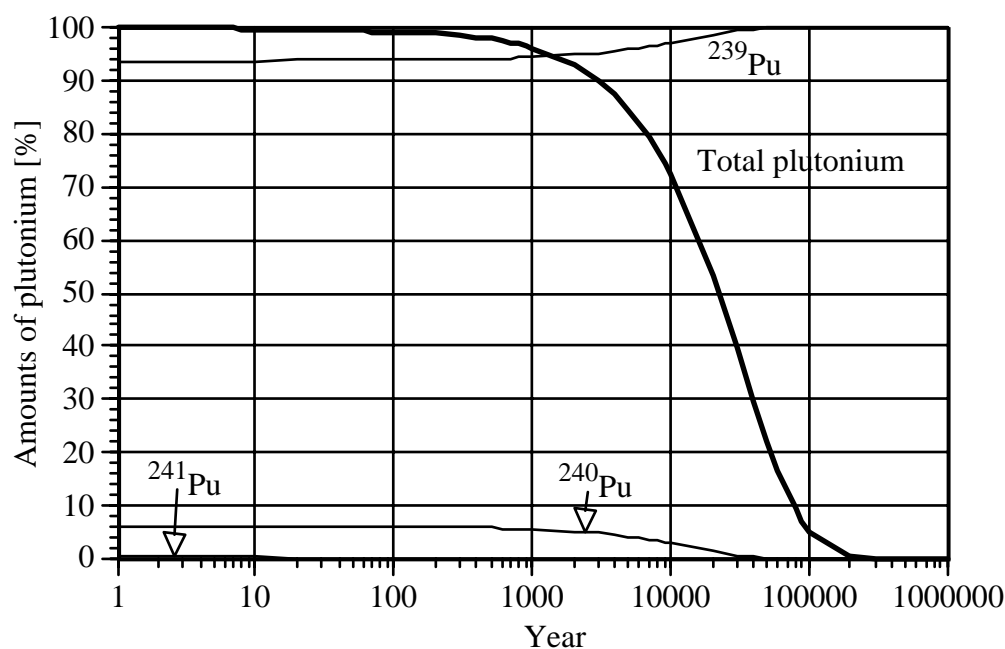


Figure 6.4a. Plutonium amounts and relative composition of weapons-grade plutonium

⁷. An alternative way of making this rough estimate is to study when the spontaneous neutron generation in the reactor-grade plutonium rises above a certain level. If the figure 70 000 years is to be used as a cut-off, the number of spontaneous fission neutrons would be a little over 660 000 $\text{s}^{-1}\cdot\text{kg}^{-1}$, as can be seen in figure 6.9a. This is a little less than twice the original spontaneous neutron background of 340 000 $\text{s}^{-1}\cdot\text{kg}^{-1}$. However, as discussed in Chapter 3, there is no absolute limit when the nuclear explosive construction difficulties arising from the neutron background become too great, so the choice of an exact limit is not possible. It also appears as though the critical mass may become a growing nuclear explosive construction problem in approximately the same time-scale, as is also discussed below.

The possibilities of using various methods of isotope separation to improve the quality of the plutonium for the construction of nuclear explosives after this time is discussed later in this chapter.

⁸. In super-grade plutonium the ^{239}Pu content is over 99% (see table 2.2).

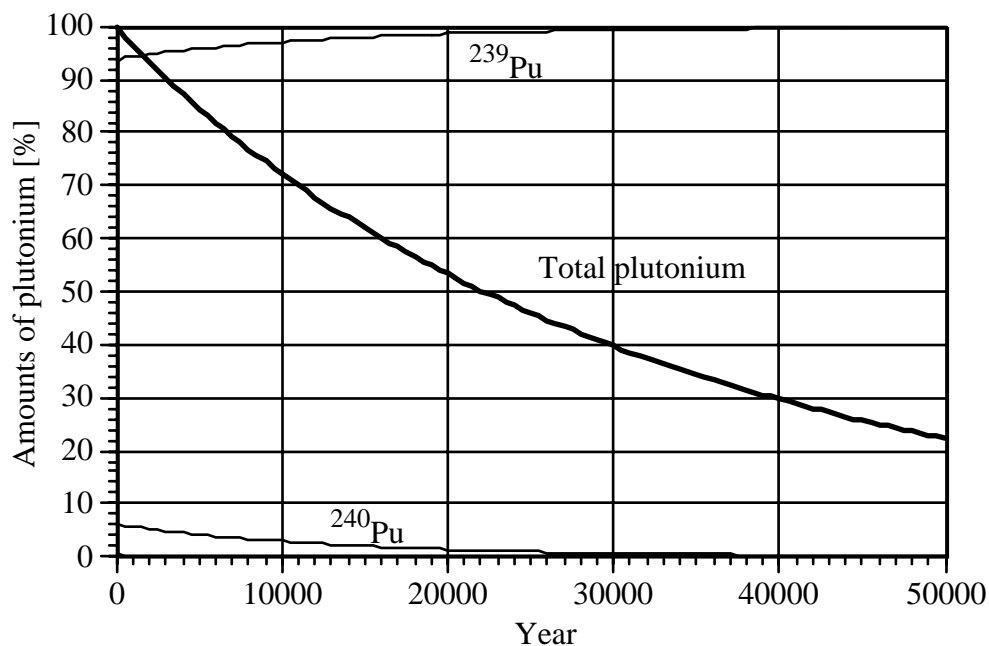


Figure 6.4b. Plutonium amounts and relative composition of weapons-grade plutonium

Finally, we can look at the long-term composition of MOX-grade plutonium. As can be seen in figure 6.5 the change in composition is very similar to that of reactor-grade plutonium that was described above.

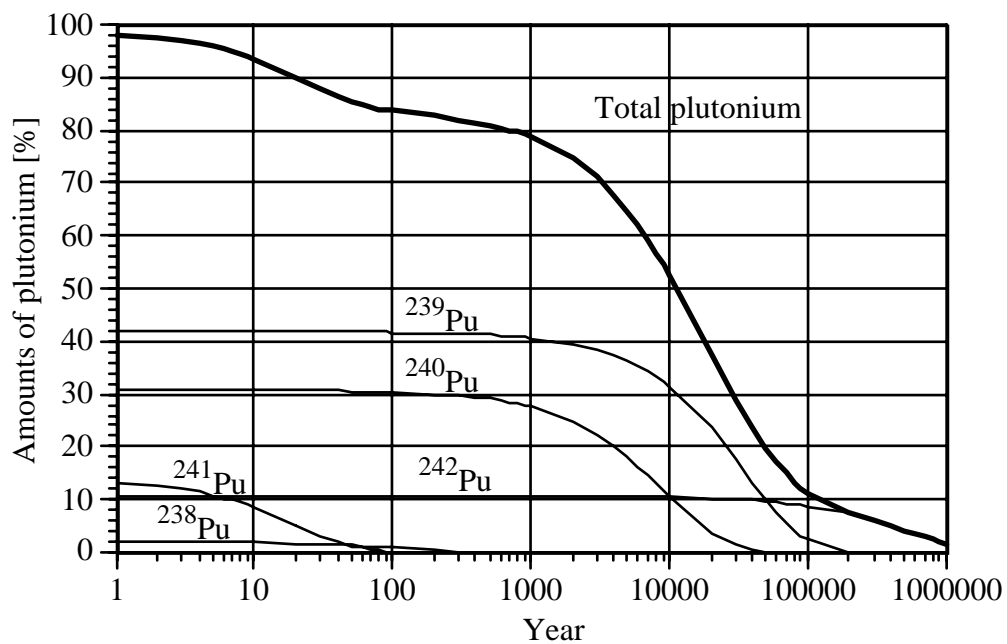


Figure 6.5. Plutonium amounts and relative composition of MOX-grade plutonium

6.1.3 Number of Nuclear Explosives

We have now studied the approximate percentages of the initial fissile material in the scenario that remains in the long term. We shall now also study what this means in absolute terms, both with regard to the absolute amounts of material that remains after a certain time and with regard to the number of nuclear explosives that can be constructed from the material. We first have to make some assumptions in order to make the calculations simpler. With the uncertainties involved in our estimates, these assumptions make little difference, especially in the long-term discussions.

First, we use one starting point in time for the calculations for all the fissile material. This means that we make our calculations as if all the reactor-grade and weapons-grade material was fresh out of the reactor at the end of the scenario, when the last plutonium has been produced. In reality both the weapons-grade and the RGPu starts to decay as soon as it is removed from the reactor, and some of the plutonium will be nearly 100 years old by this time. This will, however, only marginally effect the figures below, as only the ^{238}Pu decays with a half-life that is much less than the approximately 100 years that the plutonium is produced during in the scenario. Still, this means that the values at the lower end of the time-scales in the estimates in the figures below should be revised downwards somewhat.

Second, we assume that, because the half-lives for the uranium isotopes in the weapons-grade (highly enriched) uranium are so much longer than the time-scale in the figures, the amount of weapons-grade uranium in the scenario is essentially constant over time.

As a basis for the calculations of the number of nuclear explosives that can be constructed from the fissile material in the scenario, we begin by calculating the total amount of fissile material that remains at a certain time. We use the values from table 6.2 as data. The results of these calculations are shown in figures 6.6a and 6.6b.

As can be seen in the figures the RGPu dominates the total amount of fissile material for tens of thousands of years. Only in a longer term, i. e., from approximately 30 000 years and onwards, does the WGU dominate. This material then decays very slowly and we therefore have about 1 100 tonnes of weapons-grade uranium remaining for millions of years⁹.

We will now make an estimate of how many nuclear explosives that can be made from the fissile material created in the scenario. We use the data from table 6.2 as initial values. WGPu and WGU keep their characteristics as materials usable for nuclear explosives construction for the whole time considered in these calculations. However, as we have seen above, the composition of RGPu changes quite considerably with time and we have used the time 70 000 years as a limit when we can say that the RGPu is less suitable as explosives material. In the figures below we have set the number of explosives possible to make from RGPu after 70 000 years equal to 0. After this date the ^{239}Pu in the RGPu is still usable in nuclear explosives but (probably) has to be separated from the ^{242}Pu . This, however, as discussed

⁹. Using the thumb-rule given in note 6 about 1 tonne would still remain after 7 billion years. The enrichment grade of this uranium would, however, be greatly reduced.

below, becomes relatively easy using conventional isotope separation techniques at approximately this time-scale.

Figures 6.7 shows the number of nuclear explosives that can be constructed using the fissile material in the scenario.

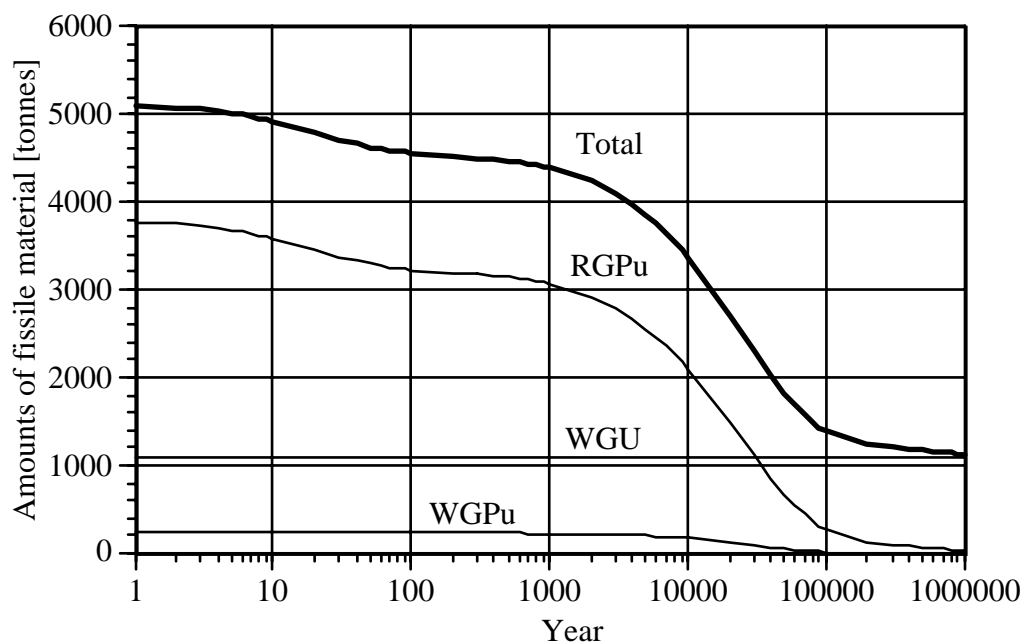


Figure 6.6a. Long-term absolute amounts of fissile material in the scenario

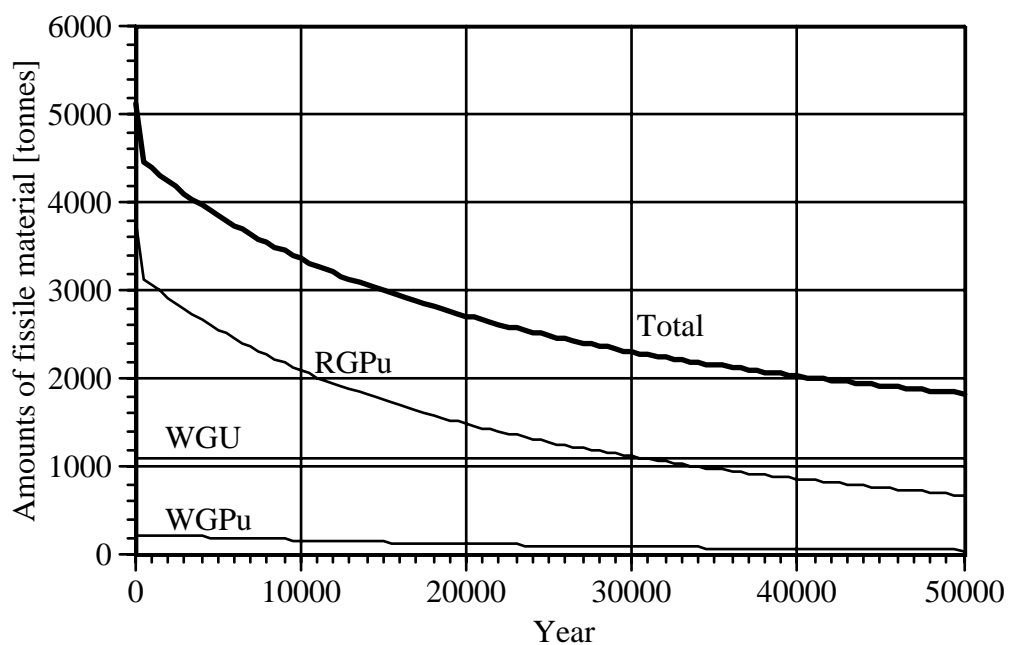


Figure 6.6b. Long-term absolute amounts of fissile material in the scenario

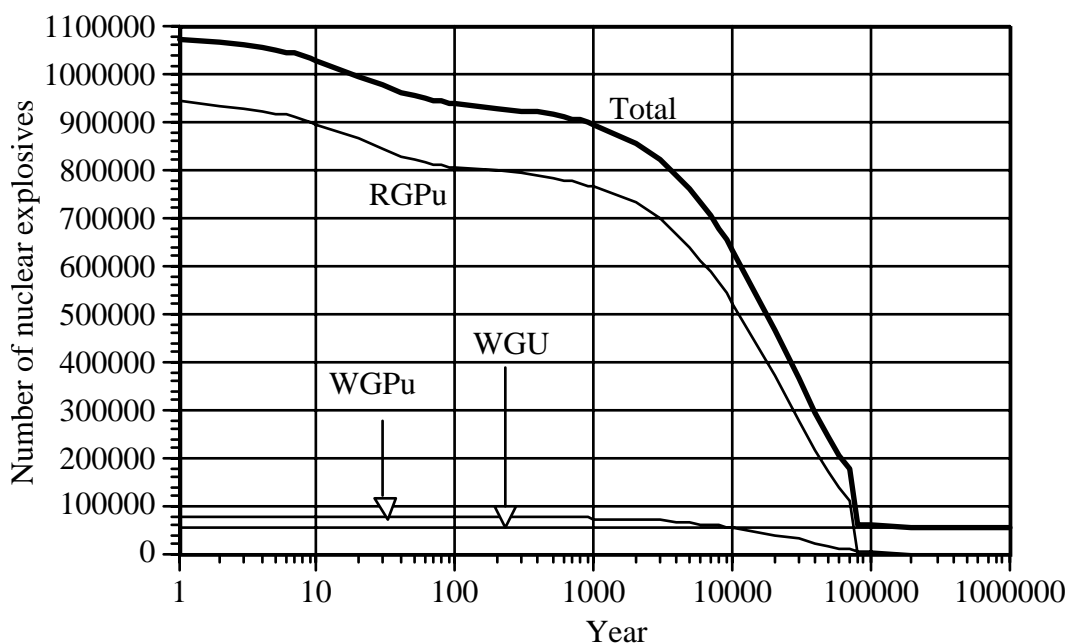


Figure 6.7. Number of nuclear explosives that can be constructed using the fissile material in the scenario

We can see that the number of weapons decrease from the initial value of over 1 million to about half that value after approximately 20 000 years. The big fall, due to the RGPu as discussed above, comes after 70 000 years and then the number levels off at a little above the 55 000 explosives that are due to the WGU. However, if the ^{239}Pu in the RGPu remaining after 70 000 years is separated out, the sharp fall is not relevant and the number of nuclear explosives that the RGPu is usable for would be higher for until after approximately 250 000 years when the RGPu would be essentially ^{242}Pu .

6.2 Changes in Construction Characteristics of Reactor-grade Plutonium in Nuclear Explosives

As discussed in Chapter 3, several factors influence the possibilities of using plutonium as a material for the construction of nuclear explosives. We discussed the possibilities of using RGPu for the construction of nuclear explosives and we looked at some characteristics of RGPu that make the material less usable for such purposes than WGPu. We did, however, find that most such difficulties can be overcome to a certain extent, especially if the construction group has access to high-technology research and development tools and advanced expertise in metallurgical and explosive technology. This means that small-sized nuclear explosive that have relatively high reliability can be constructed using RGPu.

Because the isotope composition of RGPu changes over time, as shown above, one can expect the characteristics of RGPu which are critical for the construction of nuclear explosives to change over time. We will now study a few of these

characteristics to see what influence the change in isotope composition has on them. We will first look at how the heat production in the plutonium changes, a factor that effects the metallurgical problems involved in the construction of the fissile core of the nuclear explosive. Second, we will look at changes in the neutron background, a factor that effects the problems of pre-initiation of the nuclear explosive. Third, we will discuss how the critical mass of the plutonium changes. Finally, we will look at the handling characteristics for the plutonium, i.e., the surface radiation dose rates of the plutonium metal.

6.2.1 Phase Change

As described in Chapter 3, one of the main problems when it comes to the construction of nuclear devices based on plutonium is that plutonium can exist in several metallurgical phases, each having different physical properties and a different critical mass. Because the plutonium can undergo phase changes with changing temperatures, any heating of the plutonium is a problem. Heat is produced in the plutonium by radioactive decay. Table 6.4 shows how much heat is produced in the different plutonium isotopes.

Isotope	Heat production (W·kg ⁻¹)
²³⁸ Pu	560
²³⁹ Pu	1.9
²⁴⁰ Pu	6.8
²⁴¹ Pu	4.2
²⁴² Pu	0.1

Table 6.4. Heat production in plutonium¹⁰

We can calculate how the total heat production in RGPu changes over time and compare this to WGPu. Figures 6.8a and 6.8b show the results of such a calculation.

From the figures we can see that the heat produced in the RGPu is about 5 times as large as that of WGPu as the spent fuel is removed from the reactor. This can be explained by the relatively high content of ²³⁸Pu in the RGPu. However, because this isotope has a relatively short half-life, 87.7 years, it only takes about 500 years until the heat production falls down to values close to that of WGPu and any metallurgical or other heating problems that could occur with the RGPu would not be any worse than those that are involved when dealing with WGPu.

¹⁰. Data from table 2.3.

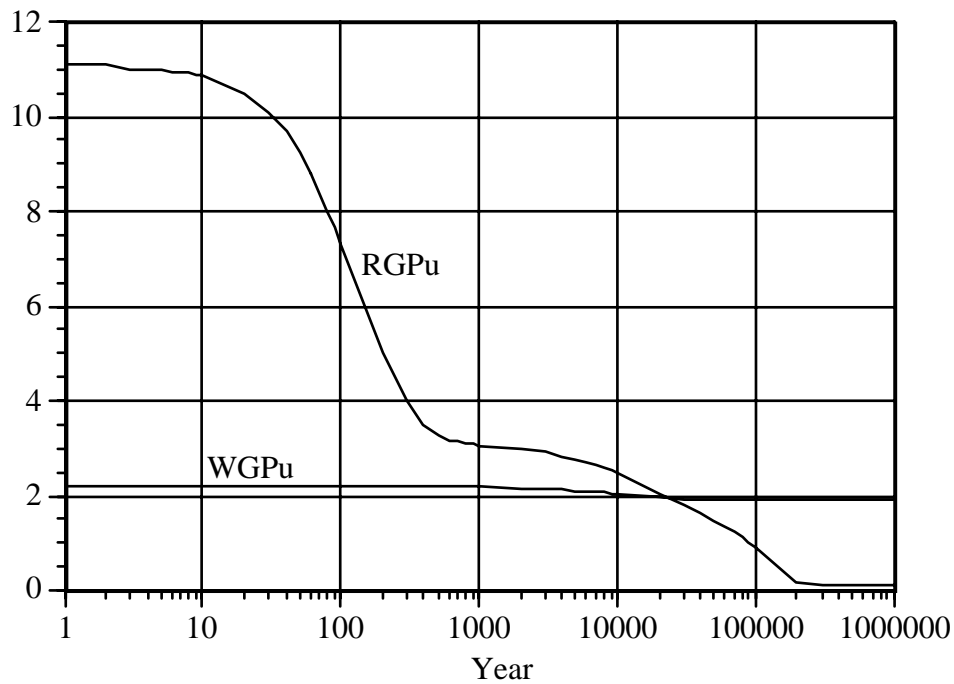


Figure 6.8a. Heat production in plutonium

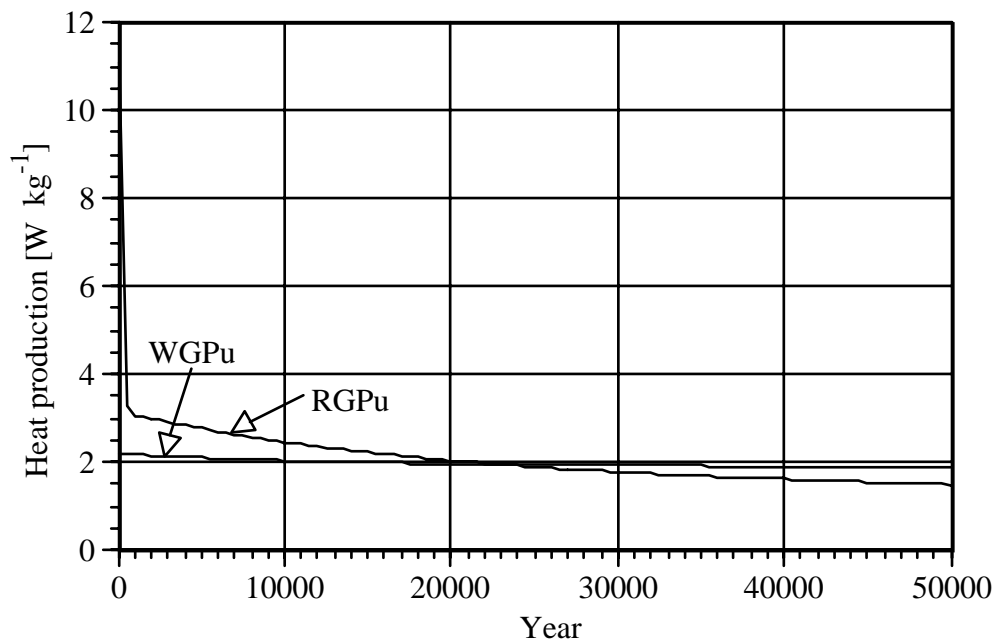


Figure 6.8b. Heat production in plutonium

Another important change is that the ^{241}Pu with a half-life of only 14.4 years very soon disappears. This isotope decays to ^{241}Am that has a relatively high specific heat production¹¹. This heat causes problems even in the WGPu in today's nuclear arsenals and is one reason why the nuclear warheads containing plutonium

¹¹. ^{241}Am has a specific heat production of 114 W kg^{-1} .

are dismantled and recycled once every few years¹². This means that the short-time stability of the plutonium, both of reactor-grade and weapons-grade quality, is greatly improved after a couple of hundred years.

6.2.2 Spontaneous Neutron Background

We have in Chapter 3 discussed how the spontaneous neutron production in RGPu is relatively high compared to that of WGPu due to the relatively large amount of spontaneous fission that occurs in the even isotopes of plutonium. We also discussed how the production of neutrons due to (α ,n)-reactions when α -particles from the decay of the plutonium interacts with low-Z impurities in the plutonium. It was shown, that the presence of spontaneous neutrons make the construction of a nuclear explosives more difficult because there is a risk of pre-initiation of the chain reaction. This means that nuclear explosives made from RGPu are less likely to have high yields and one would be less certain of which yield the device would have.

Table 6.5 shows the spontaneous fission neutrons and the specific α -activity of the different plutonium isotopes and figures 6.9a and 6.9b show how the spontaneous neutron production from spontaneous fission varies with time in RGPu and WGPu.

Isotope	Spontaneous fission neutrons [neutrons·s ⁻¹ ·kg ⁻¹]	Specific α -activity [TBq·kg ⁻¹]
²³⁸ Pu	2.3·10 ⁶	644
²³⁹ Pu	29	2.23
²⁴⁰ Pu	9.3·10 ⁵	8.51
²⁴¹ Pu	–	–
²⁴² Pu	1.85·10 ⁶	0.141

Table 6.5. Spontaneous fission neutron production and specific α -activity for the plutonium isotopes¹³

If we study the figures we see that the neutron background from spontaneous fission of the RGPu is initially 340 000 neutrons s⁻¹ kg⁻¹ and is practically constant for the first few hundred years. It then starts to decrease and reaches a minimum

¹². The plutonium is chemically processed to remove the ²⁴¹Am. This process is the main source for the ²⁴¹Am that is commonly used in commercially sold smoke detectors.

This problem might not be as large as previously thought, at least for WGPu. Apparently it has now been shown at the Lawrence Livermore National Laboratory that US plutonium cores could be recycled indefinitely without removal of the ²⁴¹Am (von Hippel 1992).

¹³. Data from table 2.3.

close to $280\,000\text{ neutrons s}^{-1}\text{ kg}^{-1}$ after approximately 17 500 years. The value then starts to increase to reach a level corresponding to the initial value after approximately 34 000 years. It then rises continuously to reach a plateau of $1\,850\,000\text{ neutrons s}^{-1}\text{ kg}^{-1}$ after about 250 000 years. The decrease in the spontaneous neutron background that should be caused by the decay of ^{240}Pu is balanced by the relative increase of the ^{242}Pu isotope which also contributes a high rate of spontaneous fission neutrons. The WGPu starts with a spontaneous neutron background of about $56\,000\text{ neutrons s}^{-1}\text{ kg}^{-1}$ and this falls with time¹⁴. We see that at no time does the neutron background of RGPu approach that of original WGPu. This means that the difficulties involved in using RGPu due to the spontaneous neutron background mentioned in Chapter 3 essentially remain with time.

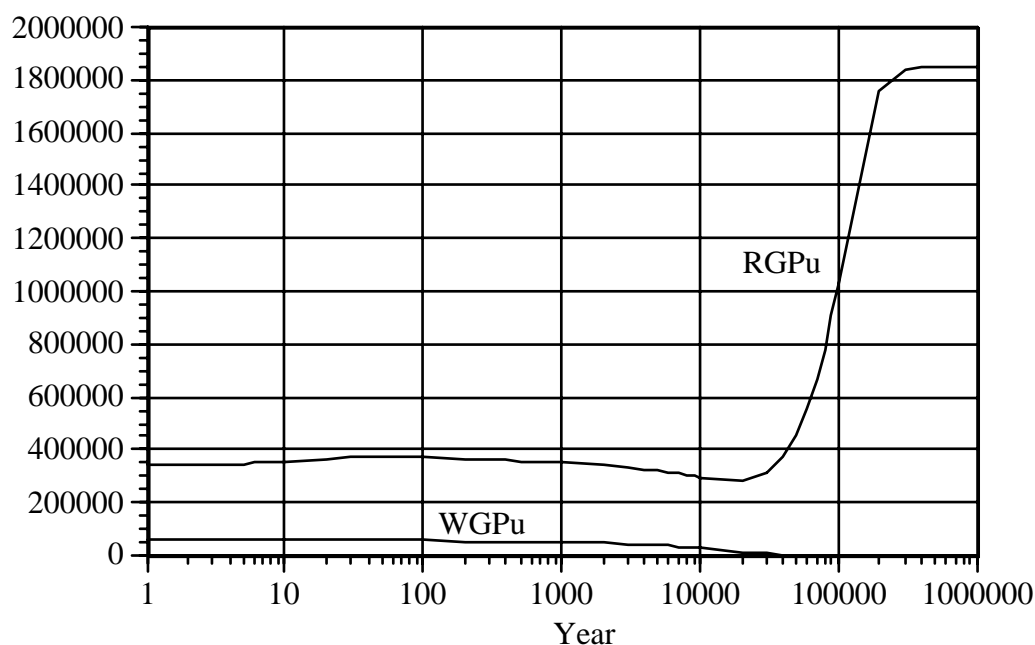


Figure 6.9a. Spontaneous neutron production from spontaneous fission in plutonium

We can once again mention the isotope ^{241}Pu that decays with a relatively short half-life of 14.4 years to ^{241}Am which has a relatively high spontaneous fission neutron emission of $1\,500\,000\text{ neutrons s}^{-1}\text{ kg}^{-1}$. This is another reason why it is often removed while recycling the WGPu in the nuclear weapons of today's nuclear arsenals¹⁵. However, because of the short half-life of the ^{241}Pu this problem disappears after a few hundred years and the short-term stability of the plutonium,

¹⁴. In the figures it seems as though the neutron background in weapons-grade plutonium is low for up to 1 000 000 years. In reality, this is not so. Because we have taken the composition of weapons-grade plutonium to contain no Pu-242 this isotope does not show up in the calculations when we discuss weapons-grade plutonium. However, small amounts of plutonium-242 exist in weapons-grade plutonium and these will also dominate the minute remains of weapons-grade plutonium that remain after 250 000 years.

¹⁵. See also note 12.

both reactor-grade and weapons-grade improves.

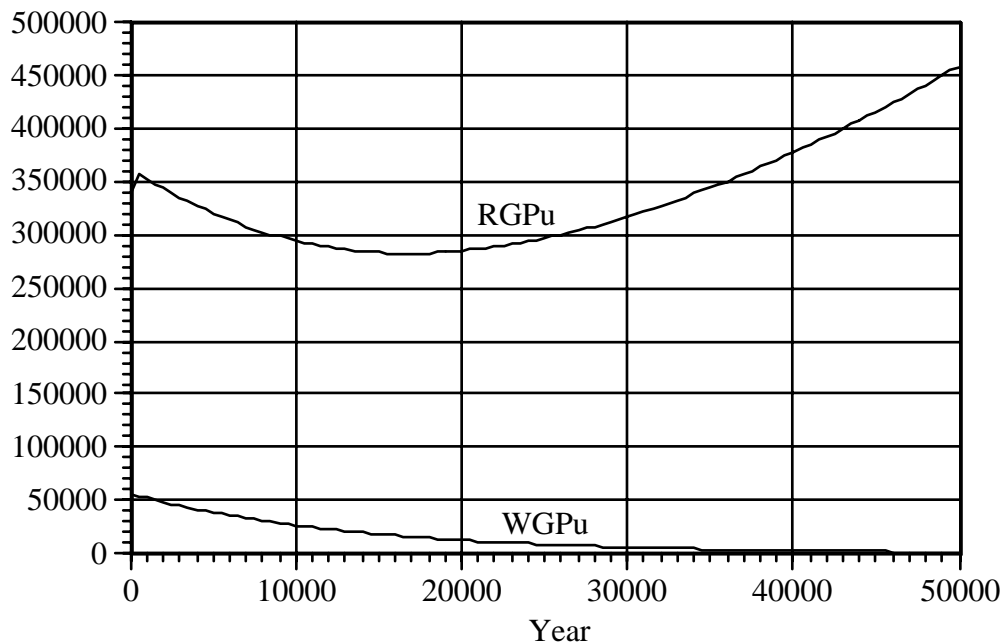


Figure 6.9b. Spontaneous neutron production from spontaneous fission in plutonium

In figures 6.10a and 6.10b we show how the specific α -activity in RGPu and WGPu varies with time.

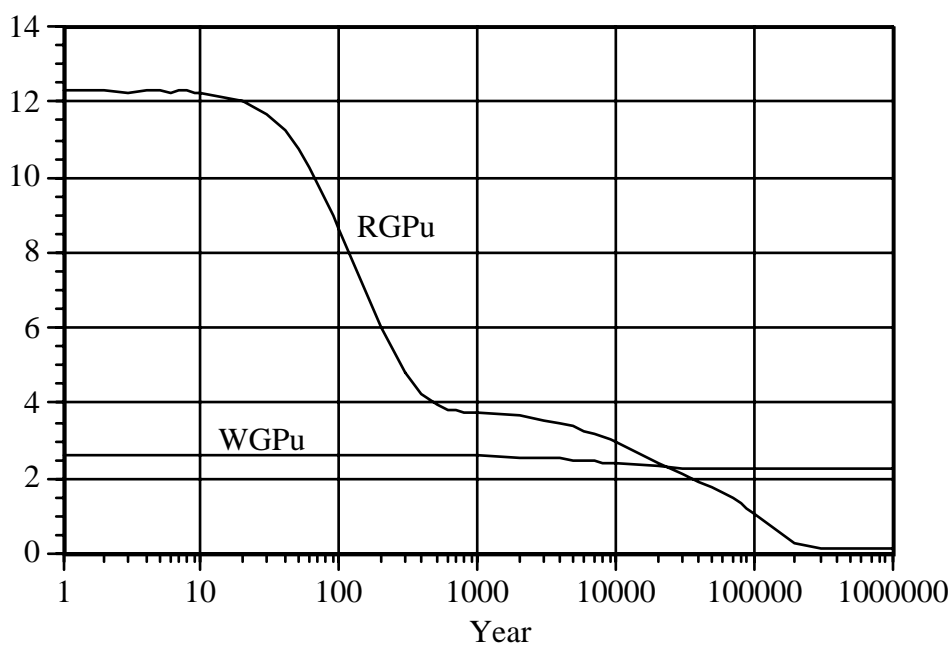


Figure 6.10a. Specific α -activity in plutonium

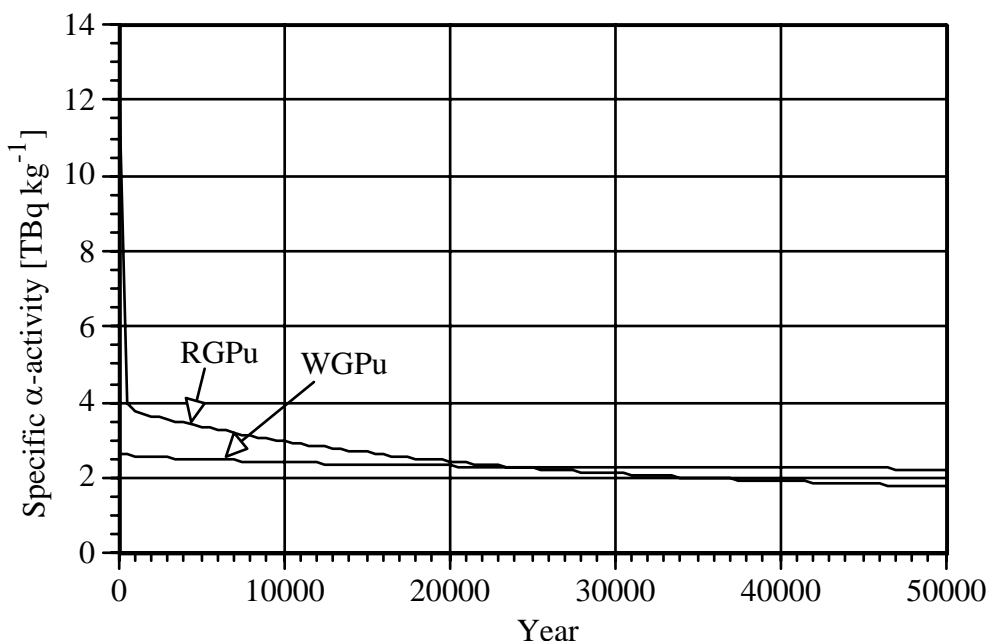


Figure 6.10b. Specific α -activity in plutonium

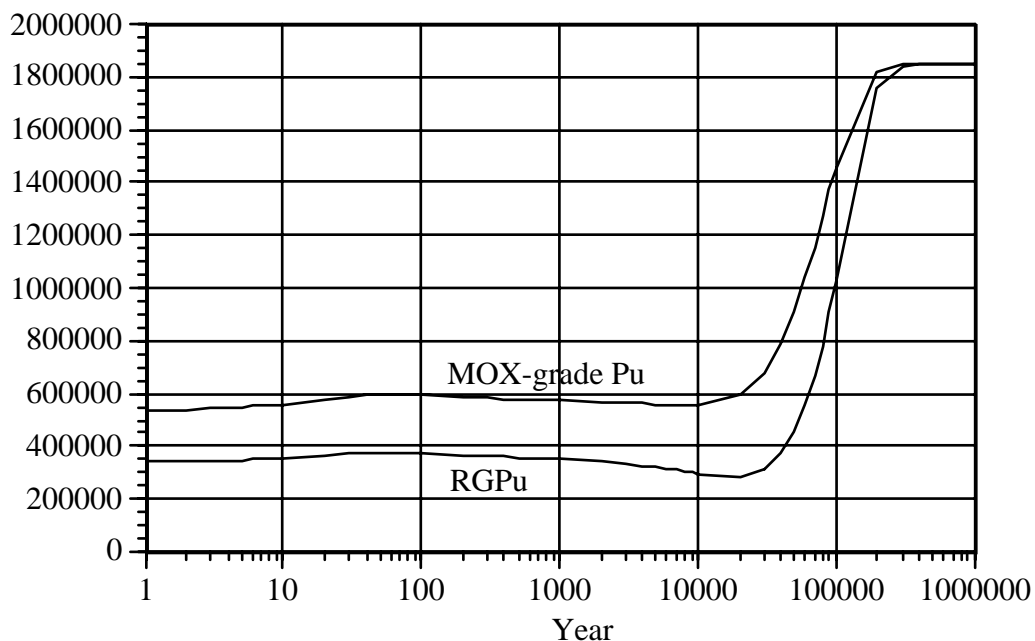


Figure 6.11. Spontaneous neutron production from spontaneous fission in MOX-grade plutonium

If we study the figures we find that the specific α -activity in the WGPu does not decrease significantly with time¹⁶ from its original value of about 2.5 TBq kg⁻¹ but

¹⁶ A similar discussion to that of note 14 can be made here. For very long time-scales, say over 250 000 years, the specific α -activity for weapons-grade plutonium will decrease due to the presence of plutonium-242 which has a low specific α -activity.

the activity in RGPu decreases rapidly during the first 1 000 years from an initial value close to 12.5 TBq kg⁻¹ to levels similar to those of WGPu. This means that the difficulties for constructing a nuclear explosive due to (α ,n) reactions in impurities with low atomic number in the plutonium decreases with time. The problems of the decay of ²⁴¹Pu to ²⁴¹Am that was mentioned in the discussions of heating and spontaneous fission neutrons is similar in the case of specific α -activity where the activity of ²⁴¹Am is relatively high, 127 TBq kg⁻¹. The same conclusions can be drawn, namely that the quality of both RGPu and WGPu is improved after the first few hundred years.

Finally a few words about the spontaneous fission neutron background of MOX-grade plutonium. Figure 6.11 shows a comparison between the levels for MOX-grade plutonium and RGPu. As can be seen, the neutron levels for MOX-grade plutonium are higher than those for RGPu.

6.2.3 Critical Mass

The different plutonium isotopes have different critical masses. To evaluate the change in critical mass with time is difficult. Mark (1990) discusses the critical mass of RGPu at different burn-ups. He finds that even at a very high burn-up, 50 000 MW_{th}·days·(kgU)⁻¹, the critical mass lies between that of ²³⁹Pu and ²³⁵U, i.e., in principle between WGPu and WGU. This plutonium would contain approximately 40% ²³⁹Pu, 30% ²⁴⁰Pu, 15% ²⁴¹Pu and 15% ²⁴²Pu plus smaller amounts of ²³⁸Pu. If we study figure 6.2a, it appears as though the relative proportions of ²³⁹Pu, ²⁴⁰Pu and ²⁴²Pu are such that the same can be said during the first 70 000 years for RGPu with our defined burn-up of 33 000 MW_{th}·days·(kgU)⁻¹. This was the point in time after we said that the RGPu was less suitable for the construction of nuclear explosives as the spontaneous neutron background had risen above that of fresh RGPu¹⁷. Thus it appears that the critical mass will not cause a large problem during this time-scale.

6.2.4 Surface Radiation

If one would want to construct a nuclear explosive, the radiation that the plutonium emits can cause difficulties because radiation shielding has to be used. The α -radiation and low-energy β -radiation is not a large problem, as using lined gloves stops the radiation. Neutrons, γ -radiation and X-rays are a bigger problem, but this is not generally regarded a problem for WGPu. This radiation is somewhat larger for RGPu. In table 6.6 the surface dose rates for 1 kg spheres of pure nuclides of different isotopes of plutonium are shown. The surface rates are those for X-rays, γ -

¹⁷. The δ -phase bare sphere critical mass is 60 kg for ²⁴⁰Pu and 177 kg for ²⁴²Pu. Mark (1990) actually uses 40 kg as the δ -phase bare sphere critical mass of ²⁴⁰Pu in this discussion.

rays and from spontaneous fission neutrons¹⁸.

Isotope	Surface dose rates [mSv·hr ⁻¹]
²³⁸ Pu	6580
²³⁹ Pu	12.1
²⁴⁰ Pu	373
²⁴¹ Pu	120
²⁴² Pu	311

Table 6.6. Surface dose rates for 1 kg spheres of different plutonium isotopes¹⁹

In figure 6.12 the surface dose rates for RGPu and WGPu are shown as they change with time. We can see that initially the surface dose rates for RGPu are over 6 times greater than those for WGPu. Although the surface dose never falls as low as that for WGPu it still falls to comparable levels for long time periods.

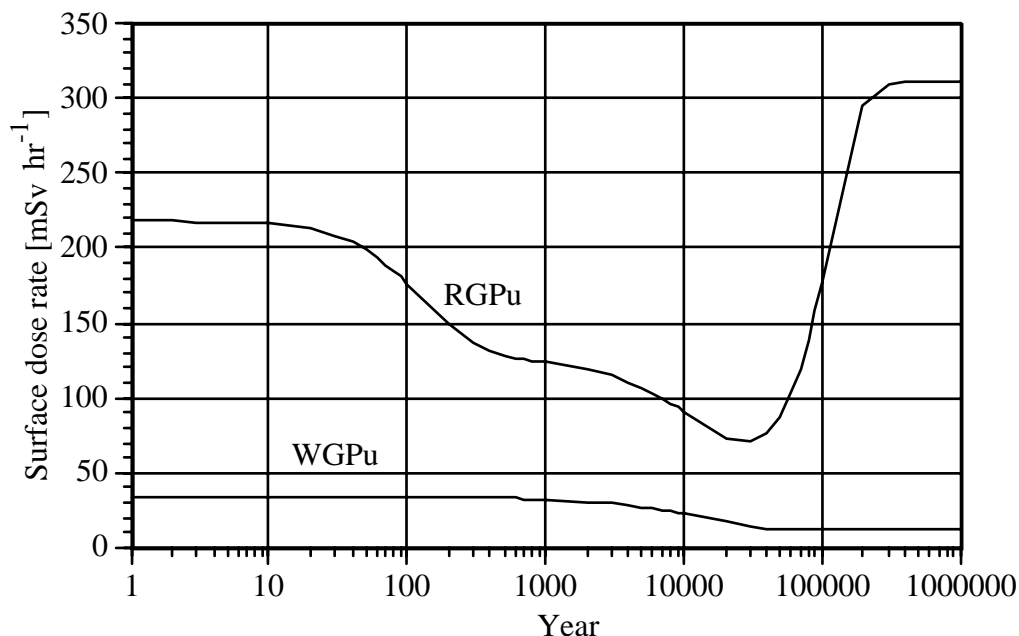


Figure 6.12. Surface dose rates from a 1 kg sphere of plutonium

Even though the radiation levels are higher for RGPu than for WGPu these are not prohibitive enough to discourage the use of RGPu in nuclear explosives. We can

¹⁸. (α,n)-reactions are not included.

¹⁹. Data from table 2.3.

also once again consider the isotope ^{241}Am . This isotope has a surface dose rate of $31\,000\text{ mSv}\cdot\text{hr}^{-1}$, i.e., a level far higher than those of the plutonium isotopes. The decay of ^{241}Pu thus also causes radiation problems, after a certain time, for the handling of a nuclear explosive. This is an additional reason for removing the ^{241}Am from the nuclear explosives regularly. This problem also disappears quite quickly in the time-scale we are discussing here as the ^{241}Pu , the source for the ^{241}Am , decays away within a few hundred years.

6.3 Changes in Accessibility of Plutonium in Spent Fuel

In the previous section we have discussed how the changes in plutonium composition of RGPu changes the construction characteristics of the plutonium. We will now discuss one further factor that changes with time and which is important when discussing the military potential of the RGPu, namely how difficult it could be to get access to the plutonium available in direct-disposal repositories of spent nuclear power reactor fuel. This spent nuclear fuel contains RGPu mixed with other actinides and fission products. In order to be able to use the plutonium for the construction of nuclear explosives, the material has to be reprocessed and the higher the radiation is from the spent fuel, the more care has to be taken with measures for radiation protection.

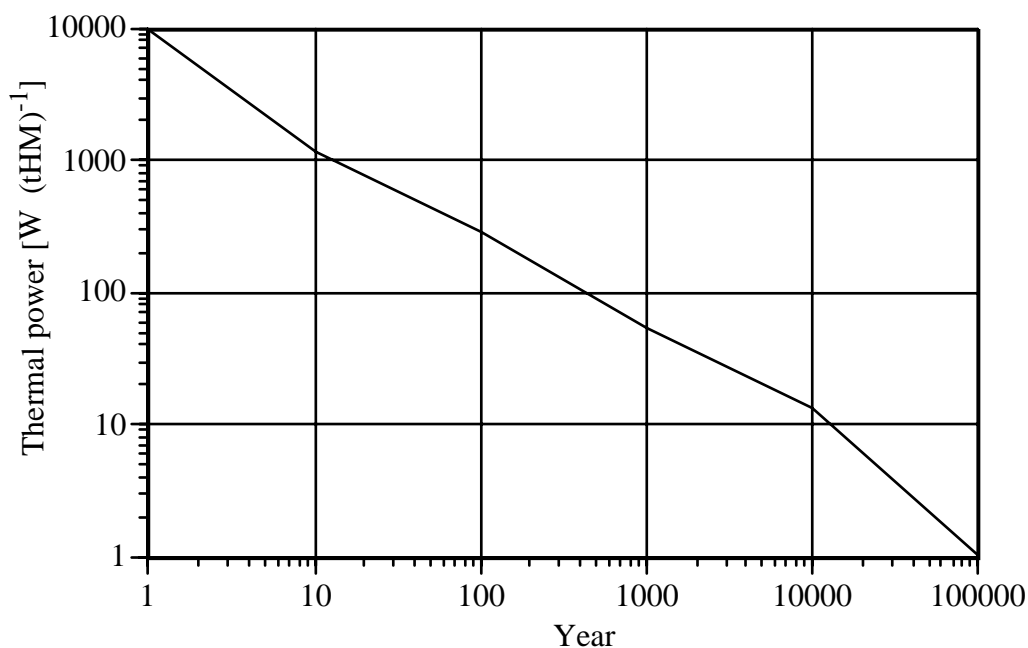


Figure 6.13. Thermal power output from spent nuclear power reactor fuel

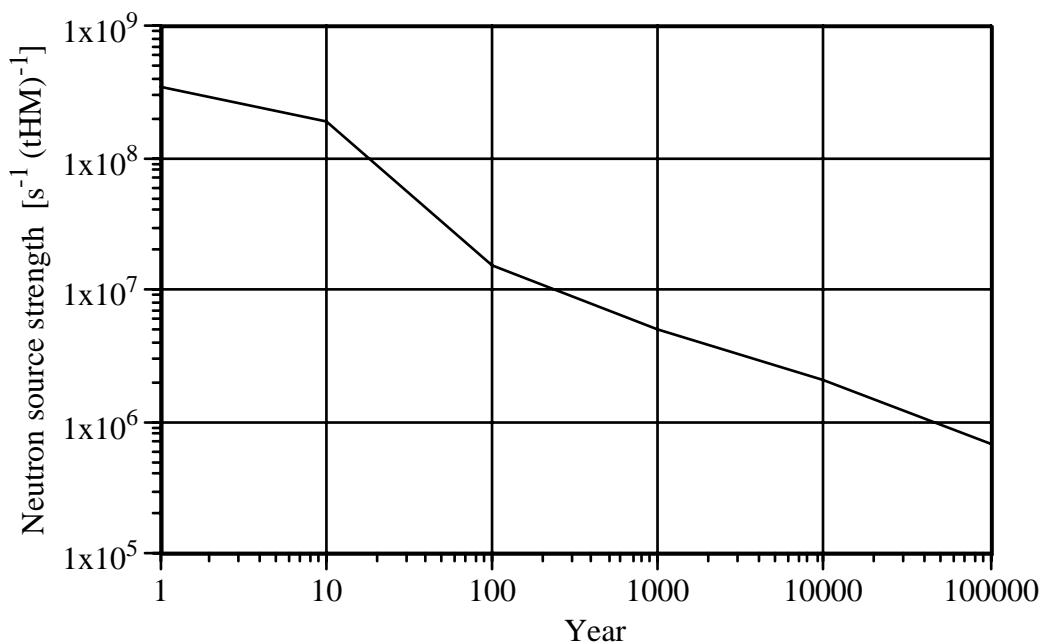


Figure 6.14. Neutron source strength in spent nuclear power reactor fuel

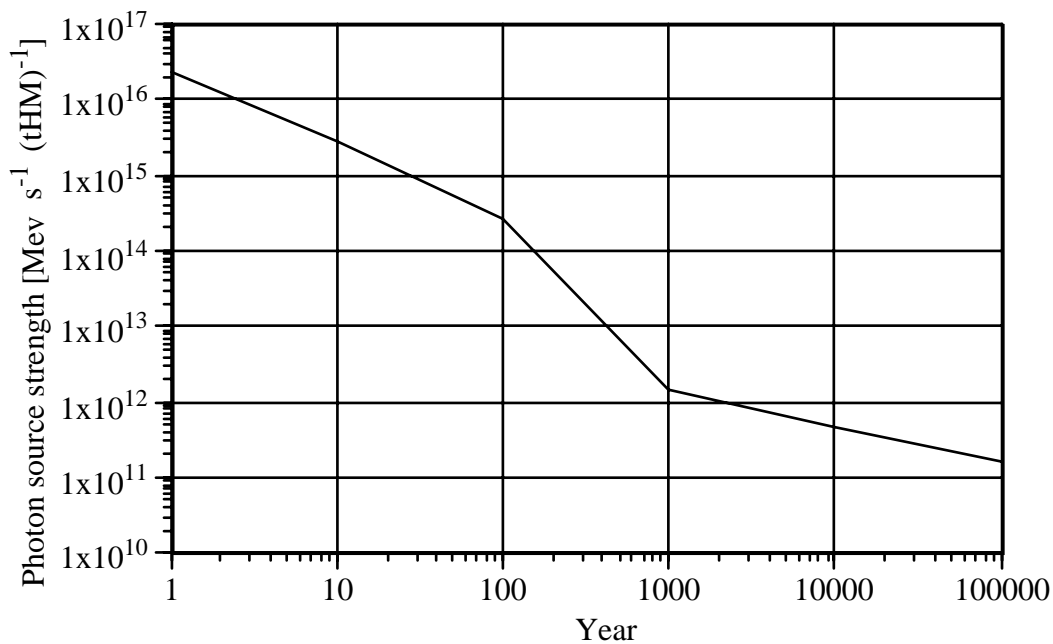


Figure 6.15. Photon source strength in spent nuclear power reactor fuel

In figure 4.1 we have shown how the activity of the spent fuel decreases with time. Figure 6.13, 6.14 and 6.15 shows how the thermal power output, neutron source strength and photon source strength from spent fuel, originally containing one tonne of uranium, from a light-water reactor (PWR) with a burn-up of 33 000

$MW_{th} \cdot \text{days} \cdot (\text{kgU})^{-1}$ varies with time²⁰. We can see that the decrease of these factors is quite considerable with time thus making it easier both get access to and to reprocess spent fuel with time.

6.4 Changes in the Potential for Isotope Separation of the Reactor-grade Plutonium

In Chapter 2 we have discussed methods for isotope separation that are used to produce weapons-grade uranium. We found that most of these methods use the mass and volume difference between ²³⁵U and ²³⁸U in the natural uranium and that these methods therefore were not useful for isotope separation of plutonium where the isotopes are closer together in mass. We also discussed how new technology for isotope separation using lasers has been developed and that these methods are usable for isotope separation of plutonium because each isotope can by itself be separated from the other isotopes.

During the whole time-scale that we are discussing now, laser isotope separation of plutonium can be used to make WGPu from the RGPu in nuclear waste, as long as there is any ²³⁹Pu left in the plutonium, i.e., up to over 250 000 years into the future. But, if we look at the isotope composition of the RGPu in the long term we see that after approximately 40 000 years we have essentially only ²³⁹Pu and ²⁴²Pu left in the material. This means that we have a mass difference between the plutonium isotopes comparable to that of the uranium isotopes in natural uranium and therefore the "conventional" isotope separation that uses mass and volume differences can be used to convert RGPu into WGPu in the long run²¹.

6.5 Summary of the Long-term Possibilities of Using RGPu for the Construction of Nuclear Explosives

We can finally make a summary of how the usefulness of RGPu for the construction of nuclear explosives changes with time:

- The heat production in the RGPu falls to levels comparable to those of WGPu after about 500 years. This means that metallurgical problems and problems concerning heating of conventional explosives are comparable to those of using WGPu after this time.
- The spontaneous neutron background remains at approximately the same level as that of the original WGPu for about 34 000 years and then starts to rise. At no

²⁰. The source for the data is Roddy et al. (1986). The neutron source is the total from spontaneous fission and (α,n) reactions. The photon source strength, i.e., X-ray and γ radiation, is given as the number of photons times the energy of the photons summed over 18 energy intervals from 0.01 to 9.5 MeV. The values given include all structural materials in the fuel rods.

²¹. The respective mass differences are $\frac{m_{U-238}}{m_{U-235}} = 1.0128$ and $\frac{m_{Pu-242}}{m_{Pu-239}} = 1.0126$

- point in time does the spontaneous neutron level approach the low values of WGPu even though there is a slight decrease in levels around 17 500 years into the future.
- The specific α -activity in the RGPu decreases to a level comparable to that of WGPu after about 500 years. This means that problems with a neutron background from (n,α) -reactions are comparable to those of using WGPu after this time.
 - There are no problems with critical mass levels until approximately after the same time period when the spontaneous fission background began to rise, i.e., after 70 000 years.
 - The surface radiation dose rates of RGPu decreases with time but never reaches as low as those of WGPu. In a very long time-scale the surface dose rates increase again.
 - The thermal output, neutron source strength and photon source strength of spent fuel in a final repository decreases with time, making the RGPu more accessible and making it easier to reprocess the plutonium. The thermal power and the neutron source strength have fallen to about 1/100 of the original levels, and the photon source strength to about 1/10 000 of the original level, in 1 000 years.

Due to the increase in spontaneous neutron background and critical mass as the concentration of the isotope ^{242}Pu rises in a very long time-scale, we have set a limit, albeit rough, of 70 000 years after which the ^{239}Pu should be separated from the remaining ^{242}Pu before it is used in a nuclear explosive. We found that such separation could be done using conventional isotope separation techniques. It should perhaps also be pointed out that during the whole time-scale we are now discussing, it is possible to convert the RGPu into WGPu by laser isotope separation.

We have concentrated our discussion in this chapter very much on the long-term characteristics of RGPu with regard to the possibility of using it for the construction of nuclear explosives, even though the WGU and WGPu have sometimes been mentioned in the text. But, it is the RGPu which is the most interesting in this context, both because of the amounts involved and because the RGPu is the material for which the characteristics change the most with time. WGU will be usable in nuclear explosives for over a million years and the amounts of WGU do not fall in any noticeable extent during the million year time-scale we have been discussing. The WGPu, though it will decrease in amounts during the scenario, will only improve as a material for the construction of nuclear explosives.

Let us now move on to the next chapter where we will examine the consequences of the long-term nuclear explosives predicament for the present planning for the disposal of spent nuclear fuel.

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7. CONSEQUENCES OF THE LONG-TERM NUCLEAR EXPLOSIVES PREDICAMENT FOR THE PRESENT PLANS FOR DIRECT DISPOSAL OF SPENT FUEL

In Chapter 6 we have shown that there is a long-term potential for the construction of nuclear explosives in the reactor-grade plutonium (RGPu) of the spent fuel from nuclear power reactors and in the weapons-grade plutonium (WGPu) and weapons-grade uranium (WGU) in nuclear weapons. As discussed in Chapter 4, present plans for high-level nuclear waste disposal are that a very large part of the RGPu will be directly disposed of as spent fuel in underground repositories, and we described the Swedish system for handling and final disposal of spent nuclear fuel as a reference method. In this chapter we discuss what the consequences of the long-term nuclear explosives predicament are for these plans. As we will show, the consequences for future generations could be quite considerable if the present plans, i.e., our reference plan, are carried through. In the next chapter we will look at some possible alternatives for the final disposal of spent fuel.

In the present plans for disposal of the spent fuel from civil nuclear power reactors, the problem of the long-term radiotoxicity of the waste is taken very seriously. In the most advanced planning, for example in our reference plan, much effort is put on not letting harmful radioactivity escape, as far into the future as 1 million years. When it comes to the long-term nuclear explosives predicament of the spent nuclear fuel in a final repository, much less effort has been put into solving it.

The reason for this is at least twofold. The first is historical. When the first plans for disposing of high-level waste were discussed, there was a general belief within the civil nuclear establishment that all waste would be reprocessed and that the uranium and plutonium in the waste would be endlessly recycled in breeder reactors or as MOX fuel. It was believed that such a plutonium economy would exist for periods of time perhaps comparable to the life-time of the waste. Essentially no RGPu would be left in the high-level reprocessing waste. There would therefore be no long-term explosives problem with the waste and there was, for example, no need to discuss the necessity for safeguards of the waste disposal sites.

The second reason is more difficult to describe, but involves psychological mechanisms. The civil nuclear complex has always shied away from discussing the connection between civil and military nuclear technology. The possibility of using RGPu for the construction of nuclear explosives has always been down-played, especially in Europe. If the plutonium in spent fuel is seen as uninteresting for nuclear explosives, then there is no reason to discuss the problem with the plutonium in spent fuel repositories. This is not the same as saying that there has been an intentional effort to underrate or conceal the problem. But, the way the system has worked, this has been the final result.

When the reprocessing and recycling of the spent nuclear fuel became uneconomical and also began to be discussed as a proliferation risk, many countries

opted for direct disposal of the spent fuel as high-level waste. Often, solutions that were intended for the high-level reprocessing wastes were adapted to instead fit the spent fuel waste. One main difference in the waste forms is the presence of plutonium in the spent fuel waste. Still, very little extra thought was given to the problem of the waste's long-term explosives potential. In addition, major interests in the civil nuclear complex did not really believe that recycling was uninteresting, and therefore regarded the direct disposal of spent fuel as a pessimistic approach that did not need much study¹.

Let us exemplify by examining our reference plan. In Sweden in the middle 1970s reprocessing was considered the best alternative for the spent nuclear fuel. Foreign reprocessing contracts were negotiated, and the high-level reprocessing wastes were to be vitrified, encapsulated and disposed of in a bedrock depository. There was therefore no need to discuss the need for safeguards of the repository as it contained very little fissile material.

As a result of the 1980 referendum that called for a shut-down of the country's nuclear power reactors by 2010, as well as for proliferation concerns, the decision was taken to forego reprocessing and to directly dispose of the spent fuel according to the KBS-3 method. In the KBS-3 report, the nearest one comes to a discussion of the long-term nuclear explosive predicament is in the following discussion (SKBF/KBS 1983, p. 21:6):

”Conceivable human intrusions that could affect the safety of the final repository may either be intentional or unintentional. An intentional intrusion into the final repository may have the purpose of recovering the useful material that it contains, i.e., the copper or the spent fuel.”

No explicit mention is made of the plutonium in the spent fuel or of any safeguard concern. In the summary volume the following statement is made (SKBF/KBS 1983, Summary Volume, p. 53):

”It must be assumed that future generations will bear the responsibility for their own conscious actions. What is of importance in this context is to provide them with the best possible information as a basis for their intrusions, i.e. to make sure information on the location, design and function of the final repository is carefully recorded and preserved. If, at some time in the future, people wish to retrieve the copper or the spent fuel present in the final repository, they will be aware of and able to cope with the radiological risk.”

There is once again no specific mention of possible plutonium use in nuclear explosives or of a safeguards problem².

¹. Actually, this is also reflected in thinking about disposal of spent fuel in repositories. Some persons believe that the repository should be constructed so that, while the repository has a long-term radiological security, it should be easy for future generations to use the plutonium as an energy source.

². The principle that “each generation must take responsibility for its own conscious actions” also allowed the SKI and SKB to remove “intrusion into a spent fuel repository for mining or waste retrieval” as a scenario that one needs to take into account for in their mutual scenario development for the SKI Project-90 (Andersson 1989, p. 131). Project-90 was a project for the development of performance assessment resources and methodology that could be used as tools for the safety

In the following we will first discuss if the long-term explosives predicament means that safeguards are needed for final repositories for spent fuel and then how such safeguards could be carried out.

7.1 Are Safeguards Needed for a Spent Fuel Repository?

There is one issue that has made the discussion of the long-term nuclear explosives predicament inevitable: the issue of safeguards. Safeguards are measures taken to prevent that fissile material is used for explosives purposes³. Even if the plutonium in the spent fuel is viewed by many persons within the civil nuclear complex as uninteresting for explosive purposes, there are severe safeguards applied to such material in order to hinder such use. Is the spent fuel in a final repository to be safeguarded? The same fissile material exists in the final repository as existed in the material before it had been put there. In recent years this subject has become more intensely discussed as the direct disposal of spent fuel has become the preferred form of disposal of high-level nuclear waste and as the date for the first repository to be built is getting closer.

The safeguarding of spent fuel under transport and in intermediate storage can be done relatively easily⁴. There are problems safeguarding the spent fuel while it is conditioned before final deposition and while the repository is being filled, but these difficulties may be solvable⁵. The main problem comes after the repository has been sealed. Can the safeguards be removed, or do future generations have to keep the material under safeguards for hundreds of thousands of years? Let us first study what the present safeguard regime under the IAEA has to say on the subject.

There are two documents that give the structure and content of the safeguard agreements that are entered between the IAEA and separate countries. The first, INFCIRC/66⁶, was first written in 1966 and is still used by some countries not party to the NPT and the second, INFCIRC/153⁷, was written in 1970 to be used by countries signing the Non-proliferation Treaty (NPT) (IAEA 1981, IAEA 1983). Concerning the possibility of removing safeguarded material from safeguards, i.e. the termination of safeguards, INFCIRC/66 states in paragraph 26 (c):

”Nuclear material shall no longer be subject to safeguards after The Agency has determined that it has been consumed, or has been diluted in such a way that it is no longer usable in any nuclear activity relevant from the point of view of safeguards, or has become practicably irrecoverable.”

INFCIRC/153 states, on the same issue, in paragraph 11 that:

evaluation of a final repository for spent fuel, i.e., to aid SKI in the licensing of a Swedish spent fuel repository (see Section 4.2.2).

³. See Chapter 9.

⁴. See for example Tkharev (1985) and IAEA (1991C).

⁵. See for example IAEA (1988B) and Stein et al. (1987).

⁶. The document has since been revised twice and is now called INFCIRC/66/Rev. 2 (IAEA 1968).

⁷. IAEA (1972).

”The Agreement should provide that safeguards shall terminate on nuclear material subject to safeguards thereunder upon determination by the Agency that it has been consumed, or it has been diluted in such a way that it is no longer usable for any nuclear activity relevant from the point of view of safeguards, or has become practicably irrecoverable.”

The question of what the term “practicably irrecoverable” means thus becomes important. If the plutonium in a spent fuel repository is considered practicably irrecoverable then no safeguards need to be applied. If not, then some form of safeguards will need to be applied indefinitely.

In addition, a comment has to be made on how the IAEA safeguards are presently carried out. IAEA relies on material accountancy for its safeguards procedures, with containment and surveillance as important complementary measures. Nuclear material is to be available for periodic inspections. For a closed spent fuel final repository, material accountancy is not possible. Therefore new IAEA procedures have to be developed for such a repository, based on containment surveillance. There has been a hesitation from the part of IAEA to accept surveillance and containment as sole safeguard measure⁸, and the IAEA safeguards agreements with member states to the Non-proliferation Treaty do not include safeguarding by facility control. However, this type of control has for a long time been established and put into practice by EURATOM (Bechtold et al. 1987, p. 8-16). It should be possible to amend the safeguards agreements so that indefinite surveillance of spent fuel repositories by suitable technologies became a legal procedure.

In the late 1970s when the International Nuclear Fuel Cycle Evaluation (INFCE) was carried out, few countries had yet opted for direct disposal of spent fuel as a final form for nuclear high-level waste. One main aim of the INFCE was to examine the proliferation risks of different fuel cycles and therefore the proliferation risk of the disposal of high-level waste was studied. In its final report the INFCE states the following when discussing the non-proliferation aspects of disposal of waste and spent fuel (INFCE 1980A, p. 30):

”... only spent fuel from once-through fuel cycles will be an item to be considered as regards the possibility of diversion, as its underground repositories would become an increasingly attractive target for diversion owing to their large content of fissile material and their decreasing radioactivity.”

Working group 7 of the INFCE specifically studied waste management and disposal and in the main final report of the INFCE it is stated, when discussing the safeguarding of waste disposal repositories (INFCE 1980A, p. 43):

”... Working Group 7 concluded that, because of their relative unattractiveness for the production of nuclear weapons, most categories of nuclear waste are likely to meet the IAEA criteria for termination of safeguards prior to their disposal. An exception is spent fuel from once-through fuel cycles, which, though initially unattractive because of the radiation barrier, becomes more accessible with time. Safeguarding of spent fuel, which is contained in canisters and thus amenable to item

⁸. See, for example, von Baeckmann & Powers (1981).

accountability and inventory verification, would be relatively straightforward during transport and emplacement in the geologic repository. Following that, successive backfilling of emplacement holes, storage rooms and galleries would provide increasing containment. After closure of the facility, even very cursory surveillance would ensure timely detection of diversion operations since these would require massive mining equipment, a large work force and surface disposal of mined rock and earth. However, the surveillance effort will extend over an indefinite period⁹.”

In its own summary Working Group 7 states approximately the same thing, but leaves out the part that states that the surveillance effort will extend over an indefinite time (INFCE 1980A, p. 234 and INFCE 1980B, p.12).

In a paper prepared by the United States delegation to the INFCE, safeguards for geologic depositories were discussed (INFCE 1979). The paper discusses the long-term proliferation risks of and possible safeguard procedures after the repositories have been closed and backfilled. In addition, the amount of effort which might be required to retrieve spent fuel at some future date from a geological repository is estimated, as well as the time that such an operation might take, and the possibility that such an undertaking might be detected. In the abstract of the paper it is stated:

”With the exception of spent fuel and high-purity non-recycle uranium, fuel wastes are likely to meet the IAEA criteria for termination of safeguards.”

The paper concludes that the only possible safeguards activity of a closed final repository for spent fuel would be surveillance. The study also indicates that the recovering of spent fuel from a decommissioned repository would require substantial effort, and would be difficult to conceal.

Since 1980 several countries have decided to forego reprocessing and to directly dispose of spent fuel in repositories. But, it was not until 1988 that the IAEA decided that it was time to make a formal evaluation of spent fuel as a final waste form and the report was not published until three years later (IAEA 1991D). In the introduction of the report it is stated, when discussing safeguards, that (IAEA 1991D, p. 3):

”It might be argued that a repository containing spent fuel creates a possibility for diversion of fissile material. The existing safeguards procedures do not explicitly cover the case of a spent fuel repository, and a concept will have to be developed, at least for the operational period of the repository where access shafts are open. There appears to be little doubt, however, that effective controls could be applied for a spent fuel repository.”

The discussion of this possibility is then deferred to a report prepared for the European Atomic Energy Community under the Commission of the European Communities. In this report it is stated that (Bechtold et al. 1987, p. 8-16):

”Concerning safeguards of a repository for spent fuel both safeguard authorities assumed a clear position. On the occasion of an expert

⁹. Italics added by the author.

hearing by the Research and Technology Committee of the German Bundestag both IAEA and EURATOM declared in a written statement that they do not see insurmountable difficulties in developing a safeguards concept for direct disposal. IAEA explicitly stated that 'all factors considered, it is the opinion of the Agency that effective controls can be applied in either case' (reprocessing and direct disposal)."

In the late 1980s the problems of safeguarding the final repositories for spent fuel was finally taken seriously by the IAEA. The IAEA Department of Safeguards began studying the problem, and steps are now being taken to develop safeguard approaches and policies at the Agency (Fattah & Khlebnikov, 1990). An advisory group meeting was held at the IAEA on December 12-16, 1988 in order to advise the IAEA on the circumstances under which the agency might logically implement the possibility of terminating safeguards on nuclear material in "waste" or spent fuel in repositories by finding it practicably irrecoverable¹⁰. The advisory group concludes that (IAEA 1988B, p. 61):

"... spent fuel does not qualify as being practicably irrecoverable at any point prior to, or following, placement in a geological formation commonly described as a "permanent repository". The advisors recommend that the IAEA should not terminate safeguards on spent fuel."

For the stages up to the conditioning of the waste prior to final placement in a repository, the group considers the present safeguard measures, and adaptations of existing measures is possible. After these stages, the group recognises that further research and development is needed in order to be able to apply safeguards to the spent fuel. The advisors end by stating that they (IAEA 1988B, p. 62):

"recognise that there are technical and legal problems that have to be solved before implementing safeguards for a closed repository. It is likely that several decades will elapse before a repository is closed. The Advisors recommend that problems associated with closed repositories should be addressed, but with a low priority."

It can be expected that this subject is not brought to the forefront of priorities until a decision has to be taken when the first repositories for spent fuel are constructed in a few decades¹¹. When it is, however, it seems very unlikely that the

¹⁰. See also Stein et al. (1987), Smith & Jung (1987) and Pillay (1988) for some discussion preceding this meeting.

¹¹. In Sweden it is expected that an application for a license for a repository for spent fuel is to be handed in just after the year 2000 and that the construction start for the repository is to take place about 10 years later.

When an application for a licence to build a Swedish final repository for spent fuel is made, the Swedish Nuclear Power Inspectorate (SKI) has a major responsibility in the licensing process. In order to prepare for this, SKI has developed performance assessment tools for the evaluation of the suitability of a repository for final disposal of spent fuel. This development work has been carried out under the auspices of a project called Project-90. The final report of the project was published in 1991 (SKI 1991). Even though it is also the role of SKI in Sweden to oversee the management of Swedish nuclear safeguards, there is no specific discussion in the report of the long-term safeguard problem of a spent fuel repository. On the question of human intrusion into the repository the following is written (SKI 1991, Summary Volume, p. 4-10):

"The treatment of human intrusion into a repository raises questions that are essentially philosophical. Whilst it is possible to make calculations of risks and

plutonium in the spent fuel in a repository is classified as "practically irrecoverable"¹².

We have considered the Swedish KBS-3 method to be our reference method for direct disposal of spent fuel. As described in Chapter 4, the spent fuel, according to this method be put at a depth of 500 m. Even relatively simple mining technology can access this spent fuel, especially in the future when the radioactivity and heat from the waste has decreased. One can conclude the discussion by stating that safeguards that rely on surveillance have to be continued indefinitely for a spent fuel repository of the type considered as our reference method.

7.2 Safeguarding a Final Repository for an "Indefinite" Time

Having established that some sort of indefinite safeguard has to be established for a closed spent fuel repository of our reference method, we can spend some thinking on how this would look like. Let us start by discussing the word "indefinite". For how long will the plutonium in the spent fuel be usable in nuclear explosives? In Chapter 6 we found that for 70 000 years the plutonium as such would not decrease in quality for use in explosives and after this time the ²³⁹Pu would remain, but would have to be separated from the ²⁴²Pu. A good approximation for the time that the ²³⁹Pu will remain in such amounts that it is retrievable is about 250 000 years, approximately ten half-lives of ²³⁹Pu. In ten half-lives, the amount of plutonium has decreased by a factor of 1000. We can thus replace "indefinitely" by 250 000 years.

A few short words about how the plutonium could be recovered from a spent fuel repository of our reference type. There is no question that it is possible to mine the plutonium, even using mining technology that is much inferior to the presently available technology. There would be radiation protection problems and cooling problems, at least for the first one or two thousand years, but these would not be impossible to solve. The mining effort would be strongly helped if good information about the repository was available in the future and if the spent fuel rods were well encapsulated, providing some radiation protection, both true in the present planning

potential health effects, it is very difficult to justify the arguments used to construct the exposure models, or parameter values chosen. It is also quite evident that there is little difficulty in finding scenarios with grave consequences, definitely lethal effects of intake and inhalation, and acute effects from external radiation. It is important that it is discussed in society and among decision-makers, and development and evaluation of scenarios might have an important rôle in this process.

Many aspects of human intrusion could form the basis for lengthy discussion and there are no 'correct' answers to many of the related questions. The position anyone takes on human intrusion is inevitably personal, subjective and philosophical. If it happens, it could be very significant in radiological terms. How this question is to be reconciled is a difficult issue facing disposers and regulators, and is currently the subject of international discussion. Consequently it was felt to be inappropriate to make any calculations within the framework of Project-90."

Several of the participants of the IAEA advisory group were, however, from SKI so the problems of indefinitely safeguarding the spent fuel repositories are known to the authority.

¹². And, even if for some reason one finds that the plutonium in the spent fuel in a repository is "practically irrecoverable" safeguard measures of some sort will surely be taken anyway, also in the long term.

for our reference method.

What safeguards are possible to apply. Methods using materials accountancy are not possible to use, so one would have to rely on surveillance methods. There would probably be some indication at the surface that there are attempts to mine the spent fuel repository. This means that remote video surveillance can be used as a safeguard method. Aerial or satellite surveillance are also useful for detecting any activities. If the release of radioactivity accompanied a mining effort it could be discovered by radiation monitoring. However, it is possible that a sophisticated mining effort is undertaken that effectively tries to remain undetected at the surface. Local seismic monitoring could be effective in discovering such efforts. Some of these technologies are studied further in Chapter 9.

Finally we can say something about the costs of safeguarding a final spent fuel repository. As stated above, the amount of surveillance needed is low. Let us make a very rough estimate, in order to get an indication of the order of magnitude of the cost. Let us suppose that a minimum of one person manually keeps surveillance over a site around the clock¹³. Approximately four persons would have to be employed to do this. In present currency this would cost somewhere around USD 400 000 per year. Assume that the repository, as estimated above, needs to be watched over for 250 000 years. This would give a total cost of USD 100 billion.

The question of costs is, however, of marginal interest, unless it is decided that the costs shall be borne by the generations utilizing the electricity from the nuclear power. Such is the case in Sweden. Total future cost in 1991 for the complete and final disposal of nuclear waste produced until 2010 and decommissioning of the country's nuclear power plants was estimated to be approximately USD 7.9 billion. As was described in Chapter 2, this cost is levied as a fee from the reactor owners of about USD 0.0033 per kWh of electricity produced in the nuclear power plants. Part of the total cost is to be collected as a real interest of about 2.5% on funded fees.

The total estimated cost for safeguard surveillance of a repository is very high compared to present Swedish planning, which allows for no such costs. Following the track chosen and allowing funds to be deposited for real interest would in principle solve the problem but is of course not practicable¹⁴. Unless one finds a method to dispose of the spent fuel where the material is really practicably irrecoverable, there seems to be no solution to this problem but to put the burden on future generations.

In the next chapter we will look at some of the alternatives to present planning for the final disposal of spent fuel and explore if they can help us out of this predicament.

¹³. This could probably be reduced by technical solutions, but it is uncertain whether this would be more or less expensive. No costs are added for any procedures that would be started if an attempt to break into the repository was discovered.

¹⁴. USD 16 million at with a net yearly interest of 2.5% would generate USD 400 000 per year. The problem is more fundamental than finding a solid financial institution that would exist for 250 000 years. Net interest implies economic growth of the same magnitude. A yearly economic growth of 2.5% for 250 000 years results in an economic growth of 10^{2681} times the original level of development, an unimaginable figure.

8. METHODS FOR LONG-TERM PRACTICABLY IRRECOVERABLE DISPOSAL OF CIVIL AND MILITARY FISSILE MATERIAL

We have shown in Chapter 7 that the "present planning"¹ for the direct disposal of spent fuel from nuclear power reactors, lead to a situation where "indefinite" safeguards are needed due to the long-term nuclear explosives predicament described in Chapter 6. This is thus the case for our reference plan for final disposal of spent nuclear fuel, the Swedish system. This system is based on the ethical norm that burdens on future generations shall be minimized. In this chapter we will examine if we can find an alternative solution for final disposal of spent nuclear fuel, that does not lead to the nuclear explosives predicament. Naturally, these methods also have to fulfil high standards for long-term environmental safety. In addition, they can not be too costly.

Alternative methods for the long-term disposal of civil and military fissile material have been suggested. We will describe some of these methods and evaluate to what extent any of them can help us avoid the long-term nuclear explosives predicament. Finally, we will analyze if any method seems clearly preferable, and to what extent further research is needed in order to chose between the methods.

Let us first observe that we are not necessarily looking for disposal methods that give absolute irrecoverability of the fissile material, only practicable irrecoverability. Recovering of the fissile material for the use in nuclear explosives should thus be too difficult to be contemplated, even though there might be a theoretical chance that one could succeed in such an endeavour. On the other hand, we should be analyzing the methods not for what is practicably irrecoverable today, but for the whole life-span of the fissile material in the waste. Both the general availability of fissile material in society and the general technological know-how in the society of how to find and reclaim the fissile material can vary. For example, in a post nuclear world, one would not have fissile material, or technology for producing new such material, generally available. Thus, fissile material in old spent nuclear fuel repositories might, in that society, be more coveted than is the case in for, example, our nuclearized world, and more effort might be found motivated for reclamation of the material. Regarding the technological level, a good example is the concept of shooting the fissile material into space for final disposal. Let us suppose that the material is put in canisters and left in a solar orbit, i.e., it would revolve like a planet around the sun. Today, we would definitely consider the material practicably irrecoverable. It would take a major effort from a superpower to be able to collect the material. But, one can certainly not rule out that at some time during the long period that the fissile material is usable in nuclear explosives, i.e. for a few hundred thousand years, intensive space communications will be developed and used, leading

¹. For a discussion of what is meant by the term "present planning" see Chapter 4.

to a safeguard burden being transferred to that generation².

When we described the methods for disposal of spent fuel, separated reactor-grade plutonium and military fissile material in Chapter 4 we divided the two types into a civil and a military problem. In this chapter we will not use the same classification. Instead, we will look at the uranium and plutonium as the two separate materials, regardless whether they are of civil or military origin³. For the spent fuel, with its reactor-grade plutonium, the separated reactor-grade plutonium, and the weapons-grade plutonium the problem is very similar, but relatively difficult to solve. We will therefore start by discussing the weapons-grade uranium and then take on the more difficult issue, the plutonium.

Generally speaking, there are three main alternative approaches for avoiding the long-term nuclear explosives predicament. These are:

- Dilution
- Transmutation or "burning"
- Practicably irrecoverable disposal

The first approach, dilution, means that the material is changed isotopically so that it is not usable for the construction of nuclear explosives. This isotopic change has to be long-term to be a proper solution. The second approach, transmutation or "burning", means that the material is converted to another material or consumed in a nuclear process that leads to the annihilation of the material, thereby making it unusable for the construction of nuclear explosives. The third approach involves finding a method of disposal of the waste that is practicably irrecoverable and thus without the need for long-term safeguards.

We will now examine where these approaches can lead us in finding solutions for the weapons-grade uranium and for the plutonium⁴.

8.1 Alternative Methods for Disposal of Weapons-grade Uranium

In Chapter 4 we have described the possibility of diluting weapons-grade uranium

². As seen below, space disposal also means that the mass of the waste has to be reduced, and thus the plutonium might be put in space in pure form, thus making it relatively easy to use the plutonium in an explosive.

³. This is not the usual approach. Because of the conceptual barriers between benign civil nuclear power and malign military nuclear weapons, the discussion of combined waste disposal for the two is often avoided.

⁴. There is one possibility for consuming the fissile material that is sometimes mentioned, but will not be studied at length in this thesis. The nuclear explosives could be detonated. However, even if this is done underground, the environmental problems of spreading fission products and unconsumed actinides in a relatively uncontrolled way make these proposals less sound less serious. However they have been discussed, for example, in Bloomster et al. (1990, pp. 43-48).

Connected with these proposals are other proposals for using nuclear explosives for different purposes. These proposals are very much a question of problems of conversion of the nuclear weapon labs, both in the United States and the former Soviet Union, in a time of nuclear arms reductions. Proposed, for example, have been to use the nuclear explosives for destruction of chemical wastes (see Rauf 1992), as a fusion energy source (Szöke & Moir 1991) or even for a defence against asteroids(!). See also von Seifritz (1984) for a previous proposal for using nuclear explosives as an energy source.

(WGU) to low-enriched uranium, followed by use as fuel in civil nuclear power reactors. This approach produces reactor-grade plutonium in the spent fuel. We have seen that the present planning for the disposal of such spent fuel leads to a long-term nuclear explosives predicament. If, however, a solution is found that is acceptable, in this context, for the spent fuel, then this first approach is still valid as a method for disposal of WGU.

Let us now look at some alternatives.

8.1.1 Dilution

If WGU is diluted to an enrichment level of less than 20% ^{235}U , the uranium is practicably impossible to use directly as fissile material in nuclear explosives⁵. This means that there is possibility to dilute WGU with natural or depleted uranium so that it is no longer usable in nuclear explosives. However, the separative work in an enrichment plant that is needed in order to increase the enrichment from 20% to the over 90% of WGU is much smaller than that needed to do the same from natural uranium so that, even though there is some safety in doing this, it is not a long-term solution as safeguards for such material have to be very strict.

We have already seen that it is possible to dilute (WGU) to low-enriched uranium for use as fuel in civil nuclear power reactors⁶. However, if enough effort is put into the process, it is possible to dilute the WGU to the isotopic composition of natural uranium or to even lower levels of ^{235}U ⁷. Such material could then, in principle, be disposed of by mixing it with large amounts of other materials, (i.e., waste from mining) and then disposed of in landfills. Such landfills could, however, be attractive uranium mines for a future nuclear explosives effort and would therefore perhaps not be possible to leave un-supervised. In addition, the radiation problems that such a site would entail are not negligible. Even now, the radon problems on the Earth's surface due to high amounts of uranium in the bedrock are of a radiological concern in many areas. A landfill with relatively high amounts of natural uranium in it could give relatively large radon problems in the surrounding environment.

There is an alternative solution for the dilution of WGU. The world's oceans contain large amounts of uranium, even if at a very low concentration. If a way could be found to dissolve the WGU in the oceans, this concentration would only change very little as would the isotopic composition of the uranium in the oceans. Ocean dumping of waste is, however, generally not an acceptable way of handling man-

⁵. See Chapter 3.

⁶. This quality of uranium, if it is not used as fuel, also has a comparatively higher value than natural uranium for a future effort to gain access to nuclear explosives, because some of the separative work that is needed for re-enrichment to WGU is already done at such a level of enrichment.

⁷. Because large amounts of low-enriched uranium have been produced and used as fuel in civil nuclear reactors and relatively large amounts of WGU have been used in civil research and military naval propulsion reactors, the amounts of depleted uranium that exist in the world are so large that it could be possible to achieve isotopic levels below that of natural uranium for the stocks of WGU that exist in the world today.

made waste problems, and historically many "waste solutions" involving ocean dumping have been very far from ideal from an environmental point of view. Even though this solution for the disposal of WGU might be relatively safe from an environmental point of view, there are strong reasons to abstain from it as it might set a precedent for other, more harmful, schemes for waste handling.

8.1.2 Transmutation or "Burning"

We have already discussed the dilution and burning of the WGU in civil nuclear power reactors as a way of disposing of the fissile material. This is a type of transmutation, but unfortunately new plutonium, even though it is of reactor-grade quality, is produced in the ^{238}U of the core of the reactor.

This problem of plutonium build-up in the uranium can be circumvented if the WGU is instead used directly as fuel in a reactor. Because of the relatively low percentage of ^{238}U in WGU, the amount of plutonium created is relatively low. There are existing nuclear reactors that use WGU as a fuel. The two main types are United States naval propulsion reactors and civil nuclear research reactors. In addition, WGU can be used as fuel in the core of fast breeder reactors. Only the first of these reactor types involve a relatively large yearly consumption of WGU and with the developments on the international scene, the numbers of these are likely to decrease. It would, however, most likely be possible to construct new special burner reactors⁸, for the destruction of WGU. These reactors would be of the same type as the reactors discussed in the plutonium section below and the reader is referred to this discussion.

8.1.3 Irrecoverable Disposal

The possibilities of irrecoverable disposal of WGU are similar to those for plutonium and the discussion of these possibilities are carried out below.

8.2 Alternative Methods for Disposal of Spent Fuel As Well As Separated Reactor-grade and Weapons-grade Plutonium

In Chapter 4 we looked at the present planning for the disposal of spent fuel as well as separated reactor-grade and weapons-grade plutonium and found that the solutions that are closest at hand are the disposal of the spent fuel in underground repositories. We used the Swedish KBS-3 method as a reference method for how this can be accomplished. We found that the separated civil reactor-grade plutonium could be used as MOX fuel in present civil nuclear power reactors, even though

⁸. Such reactors need not necessarily be of any more or less conventional fission type, but could also be based on accelerator technology.

there are limitations due to insufficient MOX-fuel fabrication facilities. In addition there are economic and non-proliferation reasons for not continuing with the use of MOX-fuels. We also found that the use of weapons-grade plutonium in MOX-fuel is also a possibility, but was subject to the same objections. This meant that, at a first glance, it might seem better to try to mix the separated civil and military plutonium with spent fuel and/or with high-level reprocessing wastes, and then dispose of the resulting material as one would with spent fuel, i.e., in a mined geologic repository. However, as we found in Chapter 7, the long-term nuclear explosives predicament has not been solved in the present planning for final disposal of spent fuel as the presently planned repositories does not make the fissile material contained in the repository practicably irrecoverable.

Let us study some alternatives that might.

8.2.1 *Dilution and Denaturing*

As stated above, isotopic dilution of WGU so that it is not directly usable in nuclear explosives is possible. The same is, in principle, not true for WGPu. As seen in table 2.3, all isotopes of plutonium can, even in pure form, separately form critical masses which are relatively small. So, in principle, even if one could produce large amounts of pure plutonium isotopes, it would not be possible to dilute the reactor-grade or weapons-grade plutonium to an isotopic composition that could not be used in nuclear explosives.

However, in practice, as we saw in Chapter 3 and 6, the spontaneous neutron background, the heat production, and the radiation levels from the different plutonium isotopes also affect the possibilities of using plutonium which is not weapons-grade for the construction of nuclear explosives. These features of the different plutonium isotopes has led to some suggestions that the plutonium can be "denatured", so that it is not usable in nuclear explosives, by adding high amounts of the even plutonium isotopes⁹.

The possibilities for denaturing plutonium has been thoroughly studied by De Volpi (1979, 1982A, 1982B, 1986). He suggests that it is, in principle, possible to denature plutonium by increasing the percentage of even isotopes. Of course, one main problem with this approach is to obtain these even isotopes in large amounts. The only plutonium isotope that can be produced in relatively large quantities would be ^{238}Pu that can be produced by irradiating ^{237}Np that has been separated in reprocessing. This possibility has also been studied in different configurations, most leading to the conclusion that it is relatively costly and needs a complicated

⁹. The mixing of the plutonium with strongly radioactive substances in order to make recycled plutonium more difficult to handle and thus proliferation-resistant have been suggested (Selle et al. 1979). Such methods would make the radiation levels so high that the plutonium would be difficult to handle. However, isotopes that are highly radioactive and are to be found in abundance also have relatively short half-lives and would therefore make the method unsatisfactory in the time-scale we are discussing in this thesis. The method might, however, be of use for transports of separated plutonium in a plutonium economy.

combination of reactor types in different plutonium recycling scenarios (Campbell & Gift 1978, Heising-Goodman 1980, Waltz, Godfrey & Williams 1980, Wydler et al. 1980, Massey & Schneider 1982).

We can now ask ourselves whether denaturing reactor-grade and weapons-grade plutonium with ^{238}Pu helps us out of the long-term nuclear explosives predicament. The answer is no. The half-life of ^{238}Pu is only 86.4 years. Within 1 000 years, the ^{238}Pu would have essentially disappeared. In addition, all proposals that involve denaturing have as an underlying assumption that a long-term reprocessing plutonium economy is developed, i.e., a non-sustainable energy future in our meaning.

8.2.2 *Transmutation or "Burning"*

Let us start by restating that the original idea of using the reactor-grade plutonium in fast breeder reactors in a long-term breeder technology does not give the long-term nuclear explosives predicament¹⁰. All reactor-grade plutonium that has been and will be produced in light-water reactors, as well as any military fissile material, can be consumed in a fast breeder reactor. In addition, in a global long-term plutonium economy, there would be very large amounts of fissile material in circulation around the globe, so a few tonnes of plutonium here or there in a repository would not make an additional problem for nuclear proliferation.

Long-lived and highly radioactive reprocessing wastes are, however, produced in a plutonium economy and have to be disposed of in some way. The main idea is to dispose of these wastes in repositories. However, partitioning and transmutation¹¹ of the actinides and other long-lived waste was first seriously discussed in the mid-1970's as a possible way of reducing the problems of disposing of these wastes¹². The long-lived actinides and fission products were to be separated from the short-lived fission products and were to be irradiated in nuclear reactors of different types, both conventional and futuristic¹³. The shorter-lived fission products would then have to be disposed of in geological repositories, but they would, in principle, be

¹⁰. If this process is stopped sometime in the future there will, however, be a problem of how to handle the last cores in the breeders.

¹¹. The word transmutation means the changing of one element into another. This is, of course, constantly happening in any type of nuclear reactor. Transmutation in a more narrow sense has been used, within the nuclear power complex, as a name for methods that transform long-lived waste actinides into short-lived products that reduce the time-scales involved in the final disposal of high-level waste. This process is also sometimes called actinide "burning".

¹². At this time the planning in most countries was that all plutonium was to be recycled, and the plutonium economy was seen as the inevitable energy future.

¹³. See Wolkenhauer, Leonard & Gore (1973), Beaman (1975), Chi et al. (1976), Jenquin & Leonard (1976), NRC (1976), CEC/OECD/NEA (1977), Beaman (1978), McKay (1978), Berwald & Duderstadt (1979), Pobereskin, Kok & Madia (1978), CEC/OECD/NEA (1980), Croff et al. (1980), Liljenzin, Rydberg & Skarnemark (1980), Patrashakorn & Papp (1980), McKay (1981), IAEA (1982) and Murata & Mukaiyama (1984) for a discussion of these concepts.

hazardous only for about 1 000 years, instead of over 100 000 years¹⁴. These ideas were not carried through at this time, because the geologic disposal of the high-level reprocessing wastes was seen as a feasible solution that would imply lower costs. Also, the use of neutrons from light-water reactors for the transmutation was not found to be a workable solution and the breeder reactors and other reactors that would be possible to utilize, were only in an experimental and demonstrations phase of development or on the drawing board.

Towards the end of the 1980's these ideas resurfaced¹⁵. The main reasons for this were the problems that had been encountered in developing and localizing geological repositories for high-level waste, as well as a realization that a future fast breeder reactor plutonium economy was threatened by economical and political pressures in many countries. The possibility of waste disposal solution by transmutation was considered to be an advantage that could be used to promote the plutonium economy.

One of the countries pushing transmutation of high-level waste strongly is Japan, where much effort has been put into developing a complete plutonium recycling system where actinide burning in fast breeder reactors is seen as a possibility for reducing the amounts of long-lived high-level reprocessing waste¹⁶.

In addition, accelerator-based transmutation has been proposed as a solution to this problem¹⁷.

As discussed above, dilution of RGPu is not impossible as a way out of the long-term nuclear explosives predicament. Can the technologies discussed for the transmutation of actinide wastes remove the predicament? If we assume that the scenario described in Chapter 5 is found to be an accurate description of the future, there is a finite amount of RGPu and military fissile material which has to dispose of in a safe way. Can we do this without having to establish a plutonium economy?

If we study the possibilities for consuming plutonium, then transmutation is a possibility, at least in principle. In fact, this already takes place in a nuclear power reactor where the build-up of plutonium is accompanied by fissioning of the created plutonium. Up to approximately 35-40% of the energy released in the fuel of a nuclear power reactor comes from fissioning of plutonium. However, there is at all times a net production of plutonium in a nuclear reactor core due to the existence of ²³⁸U in the fuel¹⁸. The same is true for the burning of MOX-fuel.

¹⁴. The value of transmutation of actinides as a method for reducing the long-term radiation exposure to future generations compared to methods using geologic repositories has been questioned (Pigford 1990, Pigford 1991A, Pigford 1991B).

¹⁵. See, for example, von Küsters (1990) and Steinberg (1990).

¹⁶. This is called the OMEGA (Options Making Extra Gains from Actinides and Fission Products) Project. See, for example, JAEC (1988), Mukaiyama et al. (1990), Takada et al. (1990), Inoue, Matsumura & Sasahara (1990), Inoue et al. (1990), Inoue et al. (1991) and Takizuka et al. (1991).

¹⁷. An example is the Accelerator Transmutation of Waste (ATW) project at the Los Alamos National Laboratories (Schreiber 1990, Gibson 1991, Lawrence 1991, Science 1991, SKN 1991). The project is also described in a special section on transmutation of nuclear waste in Transactions of the American Nuclear Society (1991).

¹⁸. As discussed in Chapter 2, the plutonium quality with regards to usefulness for the construction of nuclear explosives is decreased at high burn-up of the fuel.

In order to be able to reduce the plutonium in separated stockpiles and in spent fuel, the plutonium has to be transmuted without the production of new plutonium. This can be done by fuelling a nuclear reactor core with plutonium. Apart from a few experimental reactors with small cores¹⁹, the only presently available technology for this is to operate a fast breeder reactor without its mantle²⁰.

Due to reactor safety problems, it is not possible to fuel conventional reactors with pure plutonium or plutonium oxide cores²¹. MOX-fuel cores are balanced so that the plutonium, together with the uranium, form a core which has characteristics that are as close as possible made to resemble uranium cores. It may however be possible to replace the uranium with a material that has similar reactor-physical characteristics and that may allow the construction of a plutonium "burning" core in conventional nuclear reactors.

It would also be possible to construct new reactors that would specifically be used for the "burning" of plutonium. If existing technology were to be used, a number of reactors of the Superphénix type could be constructed. It is also possible that new reactor types or accelerator-based systems could be realized that specifically were used to burn the plutonium.

All the transmutation methods that have been discussed in this section, are dependent on reprocessing for their functioning. In the reprocessing process it is not possible to separate out the plutonium completely. Today's processes allow approximately 95-97% of the plutonium to be recovered. It might be possible to increase this to perhaps 99-99.5 % with further research. This means that there will always be some small proportion of plutonium in the high-level reprocessing waste that has to be disposed of in the waste stream of the transmutation system. This plutonium could, however, from the point of view of safeguards be considered practicably irrecoverable, even in a conventional mined geological repository. The amounts of reprocessing that would have to be carried out in order to obtain amounts significant for the construction of a nuclear explosive would be enormous.

Though never thoroughly examined, it might be possible to irradiate spent fuel rods directly using particles from an accelerator to convert all the ^{238}U to plutonium and then transmute the plutonium. This would, however, use up large amounts of energy, that could only to a small extent be taken out of the process.

Let us finally state that any method that is usable for transmuting plutonium is equally usable for consuming weapons-grade uranium.

¹⁹. An example is the Los Alamos Molten Plutonium Reactor Experiment (LAMPRE) that operated from 1961 to 1964 (Burn & Bilof 1983, p. 717-718). The core was molten plutonium-iron core consisting of 90% plutonium. 23 kg of plutonium was loaded at an output of 1 MW. The control rods were external to the core.

²⁰. Beaman & Bailey (1976) and Beaman (1978) discussed this possibility for plutonium consumption in order to reduce long-term waste problems.

²¹. The main problem is with reactor kinetics due to the fast fissioning plutonium isotopes that make the core more difficult to control.

8.2.3 *Methods of Disposal That May be Practicably Irrecoverable*

We will now study some proposed methods for disposal of spent fuel that might be considered to fulfil the requirements of practicable irrecoverability. The following list of possible solutions can be made:

- Disposal in very deep boreholes
- Sea-bed disposal
- Space disposal
- Ice sheet disposal

We will now consider these, in turn. The first, disposal in deep boreholes, is described in more detail while the three latter are described more schematically.

Disposal in Deep Boreholes

We found, in Chapter 7, that the present planning for the final disposal of spent fuel in geologic depositories did not fulfil the criteria for practical irrecoverability that is required in order to avoid the long-term nuclear explosives predicament. If, however the repository were put at a very large depth, it would be more difficult to accurately reach the repository in the future. Disposal in very deep boreholes differs from disposal in repositories created with mining technology in that it is possible to place the spent fuel at much greater depths. A mined repository is typically placed at a depth of 500 m or less, while a borehole repository can be at a depth several kilometres.

The possibility of drilling very deep boreholes for the final disposal of spent fuel has been examined. Two early studies, from 1981 and 1983, have examined the possibility of using this method²². In a Danish study (Hasted & Mehlsen 1980 and ELKRAFT & ELSAM 1981), the possibilities of drilling deep boreholes into Danish rock salt domes and then place high-level nuclear waste in them for final disposal were examined²³. Figures 8.1 and 8.2 show the principles for this method. The diagrams are from different stages in planning and therefore not of identical in design, but the high-level waste was finally intended to be placed at a depth of 3 000-6 000 m.

²². See ELKRAFT & ELSAM (1981) and ONWI/BMI (1983). They are also discussed in Bechtold et al. (1987, pp. 6:44-6:47), Chapman & McKinley (1987, pp. 49-50) and KASAM (1986, pp. 79-81).

²³. Denmark has never had any nuclear power and this very ambitious study in 5 volumes can now be seen as a curiosity. There is also a critique of the method, see Aarhus universitet (1980).

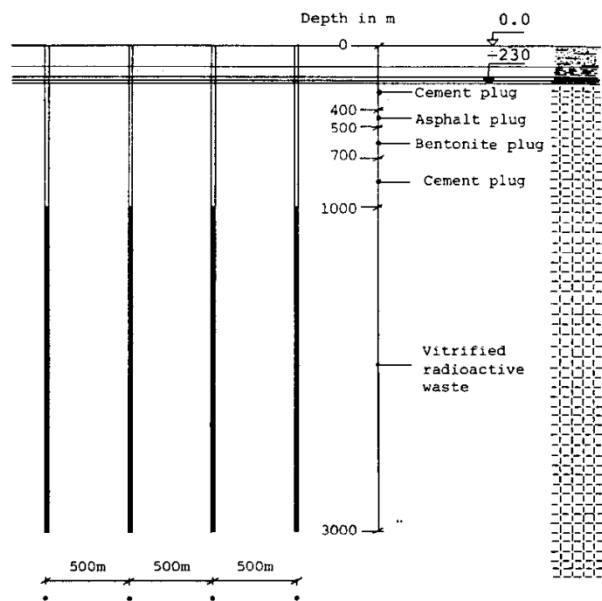


Figure 8.1. The Danish very deep borehole concept (from Hasted & Mehlsen (1980, p. 546))

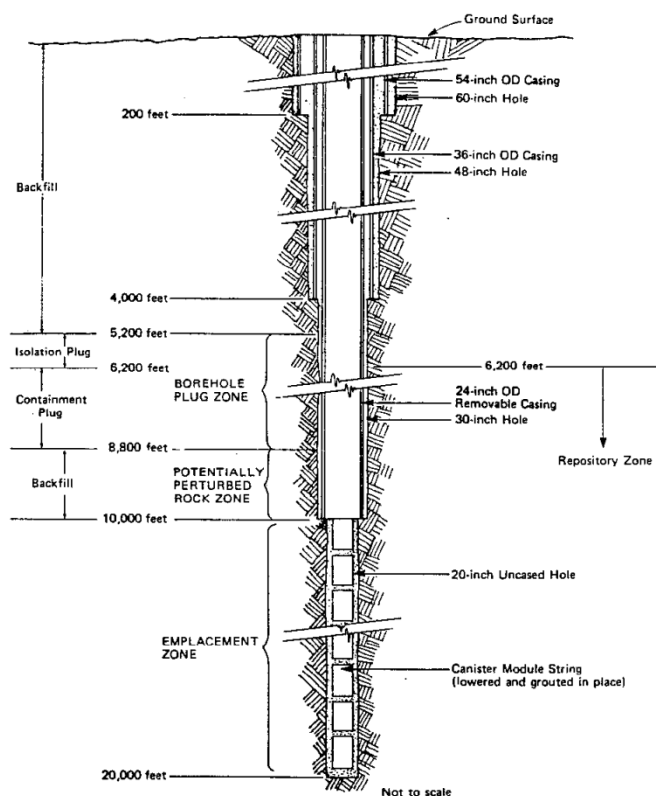


Figure 8.2. The Danish very deep borehole concept (from ELKRAFT & ELSAM (1981, p. 58))²⁴

²⁴ The actual figure shown here is from KASAM (1986, p. 81) who in turn have borrowed it from BMI/ONWI (1983, p. 5:19). The original diagram has captions in Danish.

In the United States study (ONWI/BMI 1983), the borehole extends to a depth of about 6 000 m and the waste is placed in the lower 3 000 m section. In figure 8.3 a schematic diagram of the concept is shown in comparison to a mined geologic repository.

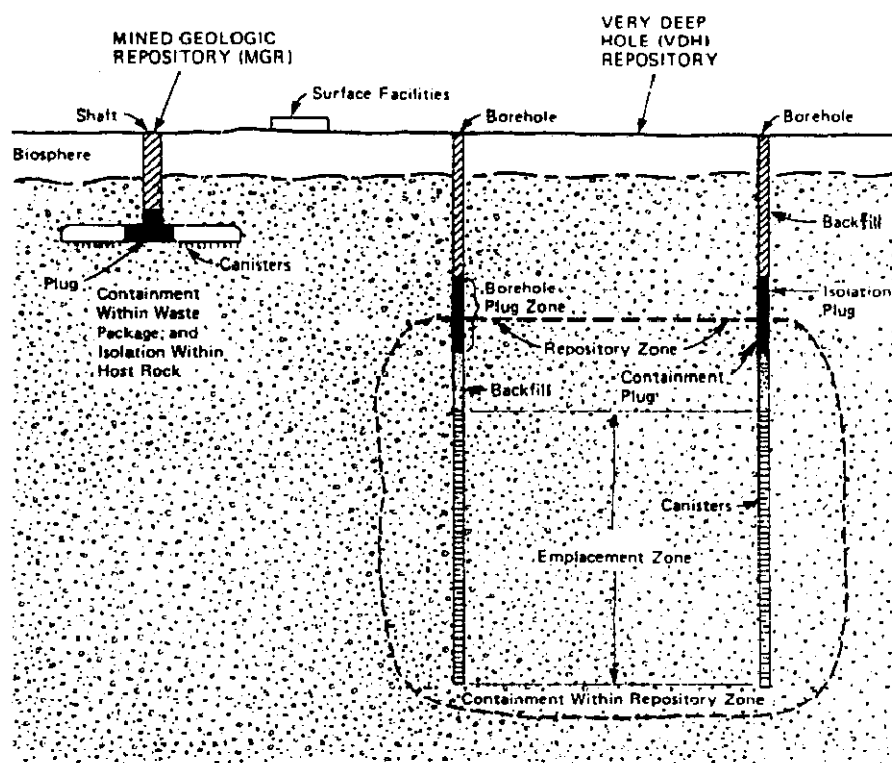


Figure 8.3. The ONWI concept

In Sweden, the Very Deep Holes (VDH) method of spent fuel disposal was developed between 1987 and 1989²⁵. The concept is similar to the two previous concepts and the objective of the method was to dispose of canisters containing spent fuel at a depth of between 2 and 4 km. A conceptual design for drilling and for deployment of canisters with spent fuel has been developed (SKB 1988, pp. 54-55, SKB 1989C, p. 48, SKB 1989D and SKB 1990B, pp. 50-52). Figure 8.4 shows a disposal option proposed for use in the method.

²⁵ Here can be mentioned two other geologic disposal methods that have been studied in Sweden. The first, the WP-Cave method, was analyzed between 1986 and 1988. The method differs from KBS-3 in that the spent fuel is disposed of in a rock chamber that as a whole is surrounded by a barrier layer of bentonite and sand. The second method, the Very Long Hole (VLH) method, involves full face boring of tunnels at an angle down into the bedrock where the canisters with spent fuel are then deposited in a bentonite buffer. The VLH method is similar to the Swiss NAGRA's Project Gewähr (NAGRA 1985). Both methods involve geologic burial at a depth comparable to KBS-3 and the spent fuel in such a depository can not be considered practicably irrecoverable. However, the VLH method might be adaptable to reach greater depths, which is probably difficult considering the technology used, full face boring machinery. The proposal has been thought of as a method of placing the spent fuel under the Baltic. This might make it more difficult to find and reopen the repository and thus make the method a practicably irrecoverable system for disposal of the fissile material.

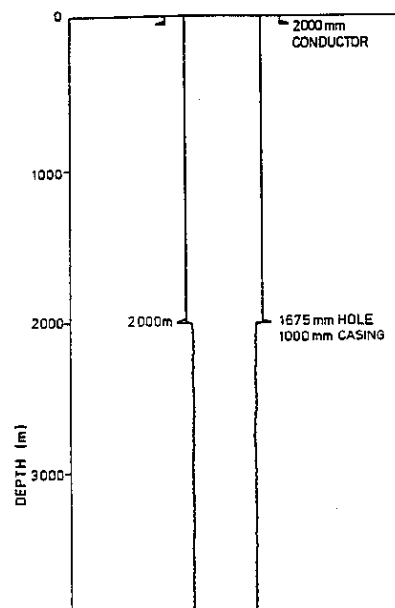


Figure 8.4. The Swedish Very Deep Hole (VDH) method (from SKB (1989D, Part II, p. 23))

The drilling technology for drilling at least 1 m diameter holes in bedrock to depths of at least 5 km exists today. Greater depths ought to be relatively readily achievable, at least in areas where the crust has a low thermal flow, as for example in Sweden. Knowledge is however lacking on the consequences for the repository of the higher pressures and temperatures and what the geohydrological conditions are like at such depths.

If the borehole were drilled to such a depth that the nuclear waste could be placed at a depth out of reach through conventional mining methods, then the repository could be said to practicably irrecoverable. To drill a new hole to that depth and reach the material is today impossible. It is difficult enough with today's technology to drill a hole to such depths that does not start to turn in unwanted directions.

There still, however, remains the question of if one could open up the hole again. Because possibility of retrieval has so far been seen as an advantage, the SKB VDH report stated (SKB 1990D, p. 83):

“It was initially thought that the VDH concept would not allow the canisters to be retrieved once they had been deployed. Further consideration of this aspect of the concept indicates this is not the case. There is no reason why the plugged section cannot be drilled or washed out with high pressure fluids. Once the canisters have been reached they could be fished out using overshot tools, a standard oil field practice.”

Research may be needed on how to make such retrieval more difficult, but the choice of materials for the plugging will probably be important.

Sea-bed Disposal

Several studies have been made of the possibilities of depositing of high-level radioactive waste/spent fuel in the sea-bed (OECD/NEA 1984, CEC 1985, OECD/NEA 1988, Calmet 1989 and Skerrett 1992). Figure 8.5 shows three methods that have been most thoroughly examined, the emplacement of waste canisters in drilled holes on the sea-bed, the boosting of waste canisters into the sediments and burial in the sea floor by freely falling penetrators.

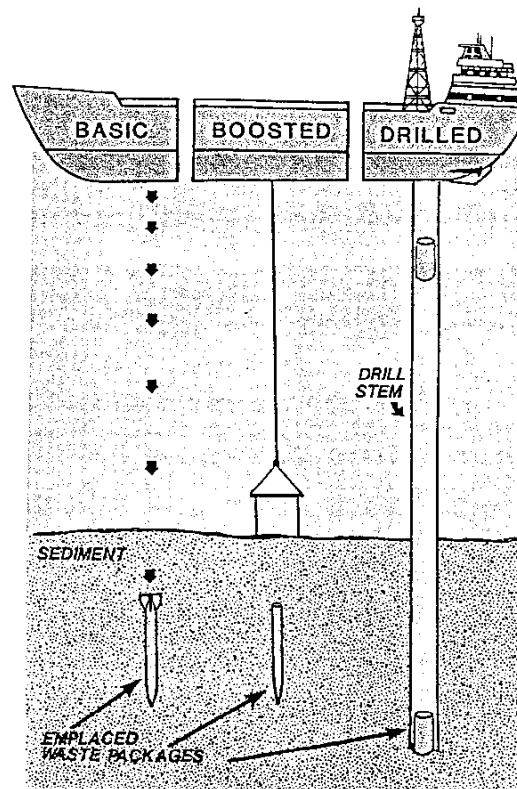


Figure 8.5. Sea-bed disposal (from Skerrett (1992, p. 22))

The sea floor would be at a depth of 3 000 to 6 000 m, the soft unconsolidated clay layer may be 50 to 500 m thick and the lithified sediment under this layer may be 20 m to 2 000 m thick. The penetrators would penetrate some tens of metres into the clay. The boreholes could continue down into the bedrock. The canisters are estimated to contain the waste for 500 to 1 000 years after emplacement. Long-term containment, for tens of thousands of years, would be provided by the barrier properties of the sediment. Finally, the ocean itself is to be a protective buffer so that dose levels to mankind in the long term do not exceed safe levels.

The OECD/NEA Sea-bed Working Group concluded in 1988 that sub-sea-bed burial of high-level waste was technically feasible, but added that long-term safety assessment required further research to reduce the uncertainties before the option is used (OECD/NEA 1988). Sea-dumping of nuclear waste is, however, not presently a publicly acceptable waste disposal solution and it is difficult to see that this will change in the near future.

It is difficult to see under what circumstances the sea-bed disposal proposals could be considered irrecoverable. As long as the canisters lie in the sediment it would not be difficult to find them by using sensing technologies that operate off the sea-floor. This would be very much more difficult if the canisters were placed below the sediments. It is conceivable that the canisters could be recovered if they were placed only 30 m into the mud. However it is possible that if the containers were put into the bedrock below the sediments that it would be possible to say that the material was practicably irrecoverable. This would depend on the depth of the holes.

Space disposal

A not uncommon proposal for the disposal of nuclear high-level waste is to send it up into space²⁶. This proposal has been evaluated by NASA in two studies in the beginning of the 1980s (Rice & Priest 1980, NASA 1982). Figure 8.6 shows the basic concept that has been proposed.

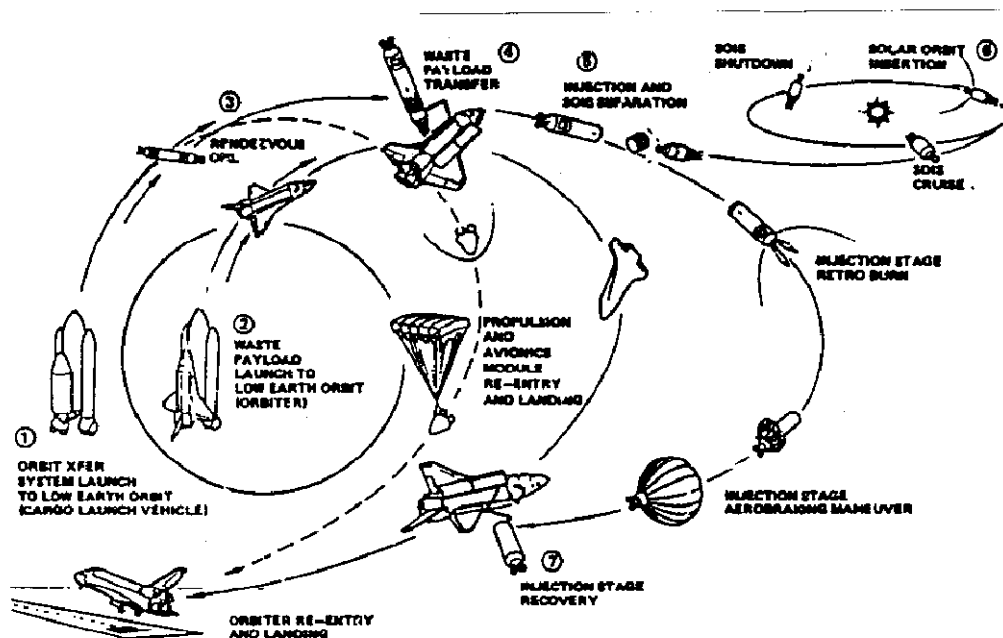


Figure 8.6. Space-based disposal

²⁶. When one discusses the problem of how to dispose of nuclear high-level waste with outside persons, a very common question is "Why don't we just shoot it into space?".

The nuclear waste is loaded into a special container that is designed to withstand the consequences of launch accidents. The load is launched into low earth orbit and then transferred to a solar orbit. It would be possible to take all the separated plutonium and weapons-grade uranium and to reprocess all spent nuclear fuel and then use this method for putting the fissile material into space.

Does such a disposal plan make the fissile material practicably irrecoverable? Even though it might be difficult to recover such a load, it would not be impossible. It is, however, very difficult to foresee how space technology and space exploration/travel will develop in the extremely long time-spans we are discussing here. It would seem that the only space disposal system for nuclear waste that makes the fissile material practicably irrecoverable would be to send the material into an orbit that would finally intercept with the sun.

Ice-sheet disposal

It has been proposed that HLW/spent fuel be disposed of in the thick ice-sheets on Antarctica or on Greenland. The heat from the waste canister would melt the ice and the canister would "fall" until it reached the bedrock. This method has not been evaluated in detail. Present international treaties forbid waste disposal on Antarctica and Denmark, to which Greenland belongs, does not have nuclear power. It is difficult to evaluate whether this method for nuclear waste disposal leaves the nuclear material practicably irrecoverable.

8.3 Which is the "Best" Solution to the Long-term Nuclear Explosives Predicament?

We have in this chapter found that the following alternative disposal methods would possibly provide practicably irrecoverable disposal of the fissile material in waste from nuclear power and nuclear weapons:

- Dilution and geologic dispersal (WGU)
- Dilution and ocean dispersal (WGU)
- Transmutation in special reactors that would not produce new fissile material (Pu and WGU)
- Transmutation in special accelerators that would not produce new fissile material (Pu and WGU)
- Geologic disposal in very deep boreholes (Pu and WGU)
- Sea-bed disposal in boreholes (Pu and WGU)
- Space disposal into the sun (Pu and WGU)
- Ice-sheet disposal (Pu and WGU)

As discussed in the descriptions of the methods above, one could have some reservations about the irrecoverability of a few of these methods. However, as discussed in the beginning of this chapter, we are not necessarily looking for absolutely irrecoverable methods, even though they have to be practicably

irrecoverable in the long term. The methods are listed in table 8.1. We can see that dilution and geologic dispersal of WGU, sea-bed disposal in boreholes and ice-sheet disposal are indicated as perhaps not meeting the criteria of practicable irrecoverability. In the case of the first method this is caused by the possibility that the diluted uranium is not dispersed enough so that it is necessary to safeguard the uranium deposit. In the case of the last two methods, this possibility has not been researched enough in this thesis to state that the method is practicably irrecoverable, or that it is not.

When deciding in which direction to look for the "best" nuclear waste disposal solution that makes the fissile material in the waste practicably irrecoverable, we will examine the methods described above in terms of cost, safety and environmental risk, and also discuss the political and public acceptance of the methods. Table 8.1 also summarizes these factors for the methods discussed in this chapter. The reference plan from Chapter 4 is used as a reference level for cost, security and environmental risks, and for political and public acceptability. We will now discuss each of these factors in more detail.

8.3.1 *Costs*

When we compare the methods in terms of cost we find one aspect especially important. The methods cannot be compared one to one. Some of the methods carry costs that are not immediately evident. The most important such costs are those that are incurred by the methods that involve reprocessing and those that involve the dilution of WGU.

All methods that use reprocessing, and where the fissile material is transmuted or disposed of separately from the reprocessing wastes, will have the costs for disposal of these radioactive reprocessing wastes, some relatively high-level and long-lived and large amounts of low-level and intermediate-level wastes, added on top of the costs that are needed for the transmutation/fissile material disposal. This essentially means that the cost of the method has to be added on top of the reference plan. In the case of the methods that involve the dilution of WGU, the cost for this disposal method has to be added to the cost for the disposal method for the plutonium. This is so because it would be possible to dispose of the uranium in the same way as the plutonium when a solution is chosen for the latter.

In table 8.1 we compare the costs of the different disposal methods with those of the reference plan.

The dilution methods, as noted above, only manage the WGU disposal problem and are therefore not cost effective, as such, even though per kg they may be less expensive than other methods. However, as discussed in Chapter 4, the WGU does have a commercial value if it is diluted to low-enriched uranium and used as nuclear power reactor fuel and may thus never, as such, pose a waste problem.

Method	Practicably irrecoverable	Costs	Safety/ environmental properties	Public and political acceptance
Reference Method (Swedish KBS-3)	No	Reference	Reference	Reference
Dilution and geologic dispersal	Maybe	Higher (Only treats WGU)	Worse Possible background radiation problems	Equal
Dilution and ocean dispersal	Yes	Higher (Only treats WGU)	Equal	Lower
Transmutation in reactors with no new production of fissile material	Yes	Higher (Reprocessing)	Worse Risk for reactor accidents High occupational exposure	Lower
Transmutation in accelerators with no new production of fissile material	Yes	Much higher (Reprocessing and new technology)	Worse Risk for "reactor" accidents High occupational exposure	Lower
Space disposal into sun	Yes	Much higher (Reprocessing and new technology)	Worse Risk for accidental release of radioactivity	Lower
Geologic disposal in very deep boreholes	Yes	Approximately equal	Equal or better	Equal or higher
Sea-bed disposal in boreholes in bedrock	Maybe	Lower, equal or higher	Equal or Lower	Lower
Ice sheet disposal	Maybe	Lower	Lower (?)	Much lower

Table 8.1. Factors to be considered when choosing a method for practicably irrecoverable long-term disposal of militarily usable fissile material

The costs for transmutation of nuclear fissile material in reactors and the space disposal of the material into the sun are generally higher than those for the geological disposal methods because of the additional disposal costs for the reprocessing waste as discussed above. Because new technology needs to be

developed and much energy is needed for accelerator transmutation and for space disposal, these will probably have costs that are much higher than the reference plan²⁷.

Geologic disposal in very deep boreholes can be done at a cost level comparable to that for the reference method²⁸. Although the technology for the drilling of deep boreholes is not as advanced as that for mining, it is advanced enough for the purpose here described already at present and there are good reasons to believe that relatively minor research and development would be needed in order to improve the technology further. In addition, it is possible that the containment properties of the bedrock at the depths we are discussing for the deep borehole method, are such that less expensive container materials can be used.

Sea-bed disposal might be a little less expensive if the methods to be used were just emplacement into the sediments, but as we have discussed above, if the method is to result in practicable irrecoverability of the material, a hole has to be drilled in the bedrock. Such a method would probably be at least as expensive as deep geological drilling, especially if comparable depths had to be reached in order to ensure practicable irrecoverability. Ice-sheet disposal, however, would probably be cheap. The "drilling" would be done by the heat from the canisters.

The cost estimates presented here are, of course, estimates relying on the present situation. If the waste disposal is not taken care of by present generations, but left to future generations, they have to redo the calculations based on their level of technological development.

The total costs for the disposal of a certain amount of high-level radioactive waste also depends on the process that is used for the research and development of the method. If the total sum available for waste disposal is fixed it can be very difficult to change the direction of the research and development from one method to another. The implications of this for our reference method, the Swedish disposal plans for spent nuclear fuel, is discussed in the final chapter.

8.3.2 *Safety and Environmental Concerns*

An important factor is, of course, whether the method also satisfies the long-term criteria for environmental security. In addition, the method, while being carried out, should not pose an environmental problem. This aspect is also included in table 8.1.

²⁷. Bloomster et al. (1990) have compared costs for different disposal methods for military fissile material. They estimate that the cost for space disposal of plutonium in a sun orbit to be on the order of USD 200 000 per kg. The total amount of spent fuel in the Swedish nuclear program is expected to be 7 800 tonnes. The cost for the disposal of this spent fuel is estimated to be approximately USD 9.25 billion. This means that the costs for disposal of spent fuel in mined geologic repositories would be approximately USD 1 200 per kg. This is however the cost for the complete Swedish waste handling system, including costs for the decommissioning of the power plants. The cost just for constructing and filling an additional repository is lower, perhaps as low as one eighth of this amount.

²⁸. In SKB (1989D, p. 85-86), the total cost for disposing the Swedish spent nuclear fuel using the VDH method instead of the KBS-3 method was estimated to be approximately two to three times higher.

We can generally see that this factor can be regarded as being a problem for many of the solutions.

In the case of dilution and geologic disposal, there are possible background radiation problems due to radon if the concentration of the diluted uranium in the ground becomes too high when the material is geologically dispersed.

Both of the transmutation methods suffer from the risk for radiation releases due to accidents in the transmutation reactor or accelerator "reactor" and the reprocessing plant. In addition, transmutation of the waste leads to occupational exposure of radiation to a relatively large group that work in the process. This has to be compared to the possible future release of harmful radioactivity from a repository method, which may, in any case, not be lower for the reprocessing wastes (Pigford 1991A).

The safety and environmental properties of the very deep boreholes method could probably be made at least as secure as those of the reference method. In the case of the sea-bed disposal in boreholes and ice-sheet disposal, the long-term integrity of the repository would probably only be equal to the reference method in the case of the sea-bed borehole, and then only if the borehole is sufficiently deep.

8.3.3 *Political and Public Acceptance*

To discuss the public or political acceptance of waste disposal technologies is very difficult²⁹. A question mark could be put after each assessment in table 8.1. I have tried to estimate the reaction of political and public opinion, at present, to the different choices of waste disposal. The reference method from Chapter 4 is used as a reference level.

There are two main thoughts underlying the public and political acceptance column of table 8.1. The first is that any method that has a risk, in the short term, for radiation release in accidents, however small this risk may be stated to be, has a lower political and public acceptance than methods that have very small short-term risks of such releases. This means that proponents of any method that uses reprocessing, nuclear "reactors" of any kind and launching of plutonium into space will have problems in convincing the politicians and public that the method is preferable. Secondly, methods that can be conceived as "dumping" of nuclear waste will also find political and public opposition. This means that the dispersal of diluted WGU in the oceans, sea-bed disposal and especially ice-sheet disposal will have problems finding political and public acceptance.

In table 8.1 we suggest that the method using geologic deposition in deep boreholes will have an equal or even higher political and public acceptance than the reference method. This will be true if there can be convincing evidence that the method would both be environmentally secure in the long term and also provide

²⁹. Carter (1987) and Berhout (1991) discuss the possibilities of creating public acceptance for the disposal of high-level nuclear waste. One can also here note that the table does not necessarily reflect the "public" opinion of scientists, especially not of nuclear scientists.

practicable irrecoverability of the fissile material in the waste, thus leading to a solution to the long-term nuclear explosives predicament.

It is, of course, possible that public opinion can change as the society develops in the future, especially in the long time-scales we are considering here. Public opinion can also be influenced by information or propaganda. It is therefore possible that high-tech solutions, such as accelerator destruction or space disposal into the sun could attract favourable opinion that will allow the economical burden to be accepted as less of a problem³⁰. If, however, the problem is to be solved in the not too distant future, we can not wait for such a change.

8.4 A Final Choice?

We have seen that the disposal of the fissile material in nuclear waste in a practicably irrecoverable way at a reasonable cost with equal or better safety and environmental results and perhaps a higher political and public acceptance may be possible with the very deep boreholes method.

There is research that needs to be carried out to verify this and also to verify that this method can achieve at least as high long-term safety and environmental security as the reference plan discussed in Chapter 4, the KBS-3 method.

The method can be used for the final disposal of all high-level nuclear waste. In principle it would be possible, because the method is irrecoverable, to put the separated plutonium and WGU into the repository without mixing it with other nuclear materials to make it more difficult to use it for nuclear explosives if it was recovered. The risks for criticality in the repository, and safeguard problems for transportation to the repository site mean that it would probably be useful if these substances were diluted with other nuclear high-level waste before being placed in containers for final storage. It might also be practical to have only one type of container to be deposited in the repositories. On the other hand such practices should not make it more difficult to verify the exact amounts of militarily usable fissile material that has been put into the repository.

A note can be added here. The very deep borehole method for final disposal of spent fuel could be implemented in bedrock under the sea-bed. The method would not rely on the sediment or ocean as a barrier and could probably be found environmentally acceptable in the long term.

8.5 Additional Irrecoverability

There is an additional possibility to improve the irrecoverability of the fissile material in the deep borehole method. It is probably possible to conceal the site of

³⁰. Such a change in opinion could, in the long term, be the result of a large-scale and successful introduction of advanced nuclear technologies. It would however seem more likely that, if sustainable technologies for energy supply and transportation are developed, both political and public opinion will opt for these.

the repository so that it would not be possible in the future to discover the closed repository from the surface by, for example, mineral prospecting or other techniques. It might then be possible to try and "forget" where the repository was placed, so that it would be unreachable for future generations because the exact position would not be known and the material would not be possible to find³¹. If effort is put into not documenting the whereabouts of the repository, then the information transferred to future generations would after several generations become a myth, not unlike that of Atlantis. Many expeditions might set out to find the repository; none would succeed. This possibility, however, stands in direct conflict with present planning in the reference disposal plan, the Swedish spent fuel disposal plan, described in Chapter 4.

A short note here to complement the note at the end of the previous section. The possibility of hiding and "forgetting" a very deep borehole repository that had been created under the sea-bed would be much larger than for a land-based site. In addition, international co-operation would be easier at such sites where no country would have to accept "foreign" high-level nuclear waste for disposal on its soil. There would, however, have to be some change in the way the use of the seas for disposal of waste is considered improper under almost any circumstance, especially in the eyes of a large proportion of the public. There has been so much neglect of environmental factors for so many years when human-created poisons have been dumped in the seas. This means that if the deep boreholes are to be drilled at sea, it has to be demonstrated that the method can be used at sea, with a very high degree of safety.

³¹. In addition, it might not be so easy to transfer such information. See, for example, Tannenbaum (1984) and Sebeok (1984). "Forgetting" the repository might actually be a preferable method also for this reason.

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9. PROSPECTS FOR THE LONG-TERM CONTROL OF MILITARY AND CIVIL NUCLEAR TECHNOLOGY

In the previous chapter we have discussed some possible solutions to the long-term nuclear explosives predicament. We examined the possibilities of finding practicably irrecoverable ways for disposal of the militarily usable fissile material in nuclear waste from civil nuclear power and from the elimination of nuclear weapons. It remains to be seen if our generation, or future generations living in a post-nuclear world, manage to find and realize such a method. Still, unless a fundamental change takes place in the use of technology, in the general view of how technology is to be used or in the thinking about global security issues, future generations will still need to deal with the problems of nuclear proliferation in their times, i.e., they will need some sort of safeguards regime. The situation may or may not be as serious as in today's world and in the very long time-span we are discussing, the situation may change many times, for the better or the worse. However, if global energy use develops in a direction where renewable and sustainable energy sources can be relied upon to supply all energy needs, a post-nuclear world is a probable development, and such a world would provide very good possibilities for controlling nuclear proliferation. If, in addition, the long-term nuclear explosives predicament is handled and solved by the generations living in the nuclear world, a very advantageous situation for control of nuclear proliferation will exist in such a post-nuclear world.

There are several reasons for such an advantageous situation. Both the mechanisms that will exist in a regime for the control of nuclear proliferation and the safeguard technologies that can be used by such a regime will be aided by the existence of a post-nuclear world.

Regarding mechanisms, it should not be difficult to find international agreement on the need for a strict safeguard regime that would rely to a great extent on on-site inspections of suspicious activities. Any state that might be resistant to such a regime would come under intense scrutiny by the international community. There would, in addition, be no complications regarding the dual use of nuclear technology, as there would essentially be no civil use of nuclear technology. Any country that would show any unusual interest in what is today labelled dual-use nuclear technology would come under equally harsh surveillance¹.

Regarding safeguards technology, there will also be some new possibilities. First, satellite surveillance technology delivering high resolution imagery can be fully used by an international safeguards body. Second, in a post-nuclear world the release of radiation from nuclear activities would be relatively easy to detect and a system of monitoring stations could thus be established that would have a high probability of discovering covert nuclear activities. Third, in order to facilitate the detection of a covert nuclear explosives program while on-site inspections are being

¹. This can actually be said to be the case already now. If a new country were to announce an ambitious civil nuclear programme today, there would be intense suspicions of plans for a covert military programme. The economy of starting a new nuclear power programme is so poor that it is no longer credible; thus it can hardly function as a cover for a military programme.

carried out, a system for remote detection of nuclear explosives and other nuclear materials at relatively short distances could be developed.

In this chapter we will give a brief presentation of the presently existing safeguards regime and then discuss what possible changes and improvements in the mechanisms and use of safeguards technology that could be made as the world develops towards a post-nuclear world.

9.1 The Present Nuclear Safeguards Control Regime

The main goal of a safeguards regime is to detect, in time, the diversion of what is called “significant quantities” of fissile material for the use in nuclear explosives, i.e., the prevention of nuclear proliferation². The present nuclear safeguards regime is primarily constructed around the Non-proliferation Treaty (NPT) that came into force in 1970 and around the International Atomic Energy Agency (IAEA) that was established in 1957. Each signatory of the NPT that is not an “official” nuclear weapon state has to conclude an agreement with IAEA on the safeguarding of all nuclear material of military significance owned by that country, so-called full-scope safeguards. The IAEA has the right to make on-site inspections at sites where the country has declared that it stores such material, in order to detect the diversion of nuclear material. Material accountancy is the most important method used for safeguards and it is complemented by containment and surveillance, i.e., the use of seals and remotely controlled video cameras. The NPT has been signed and ratified by about 140 countries in the world, but several countries are not parties to the treaty, many of them countries that have nuclear power programmes³.

There are other components of the global safeguards regime. In order to have some control over the trade of nuclear technology in a world without general full-scope safeguards, the major suppliers of nuclear materials and facilities have formed an informal group that has adopted guidelines for the export of such merchandise. This group is known as the Nuclear Suppliers Group or the “London Club” and one of its most important roles has been to draw up a “trigger list” of sensitive materials, equipment and technology that need to be safeguarded. Another organization that has a role concerning safeguards is EURATOM, which co-operates with IAEA in safeguarding the Western European civil nuclear programmes⁴. In addition, many countries have national policies that restrict the transfer of nuclear technology, for example, restrict exports only to countries that accept full-scope safeguards.

². There is an abundance of literature on the prevention of proliferation of nuclear weapons and on safeguards. The reader is primarily referred to Spector (1984), Goldblat (1985), Spector (1985), Eriksen (1987), IAEA (1987), Spector (1987), Spector (1988), Reiss (1988) and Spector (1990A). A sample of earlier works of importance include Willrich & Taylor (1974), Sanders (1975), Taylor (1975), OTA (1977), Scheinman & Curtis (1977), Barnaby et al. (1979) and SIPRI (1980).

³. These include Israel, India, Pakistan, Brazil, Argentina and others. South Africa has recently decided to sign the NPT. The end of the cold war and the increasing worry about the long-term stability of the present non-proliferation regime has recently prompted the two nuclear weapon states, France and China, that previously were not part to the treaty to join. It is expected that the new states that evolve as a result of the disintegration of the former Soviet Union will sign the NPT.

⁴. See, for example, Howlett (1990).

If one expands the concept of safeguards regime to encompass non-proliferation in general, there are two other important factors that effect efforts to prevent the spread of nuclear weapons. These are nuclear-weapon-free zones (NWFZ) and nuclear disarmament and arms control negotiations. The first of these, NWFZ, have been created both internationally and regionally. Internationally, NWFZ have been established, by treaty, in Antarctica, in outer space, and on the sea-bed and ocean floor. Regionally, discussions have been carried out in many areas of the world, but only two zones have been established. These are the Latin American NWFZ set up by the treaty of Tlatelolco and the South Pacific NWFZ set up by the treaty of Rarotonga.

The result of nuclear arms control and disarmament negotiations also have a more or less direct influence on the risks for nuclear proliferation. One important factor is the existence of article VI of the NPT where the nuclear weapon states resolve to strive “in good faith” for nuclear disarmament. The lack of important results in such efforts during the 1970's and 1980's caused criticism from some non-nuclear weapon state signatories of the treaty and therefore weakened the respect for the treaty. In addition, some countries have seen the NPT as discriminatory in that only some countries are “allowed” to have nuclear weapons. The reluctance of the nuclear weapon states to de-emphasize the role of nuclear weapons and to seriously discuss a global nuclear disarmament has made it more difficult to restrain threshold countries from developing a capability to acquire nuclear weapons .

9.2 Possible Future Improvements in Mechanisms

The recent developments that decrease the significance of nuclear weapons in international relations can be seen as important for future possibilities to hinder nuclear weapons proliferation. The massive cuts in the nuclear arsenals and the limitations in the deployment of nuclear weapons that have been initiated by the United States and the former Soviet Union are important in this respect as they signal the start of a revaluation of the role of nuclear weapons on the international arena. This could be the first step towards a nuclear-weapon-free world, i.e., the military part of the transition into the post-nuclear world that was described in earlier chapters. These developments can be followed by several others.

First, a formal decision should be taken by the nuclear-weapon states to cease production of fissile materials for nuclear explosives and to ban the new production of such material⁵. This could then be formalized as an international treaty. It is also important that the nuclear-weapon states put all their nuclear facilities that are civil, or that have been military but have been shut down, under international safeguards. This would put a great pressure on the countries that have seen the NPT as being “discriminatory” to follow suit.

Second, the time has now come to conclude negotiations on a comprehensive

⁵. Proposals for the banning of production of fissile material for nuclear explosives have been put forward as was mentioned in Chapter 5. In addition the United States and the former Soviet Union have, in practice, already stopped such production.

nuclear test ban and to realize an international treaty on such a ban⁶. This would signal the lessening importance of nuclear weapons and would also to a large extent hinder the strongly criticized vertical nuclear proliferation of nuclear weapons within the nuclear weapon states. The realisation of these two arms control mechanisms would also strengthen the possibility of gaining increased respect for the NPT as they can be seen as important steps to fulfil article VI.

The strengthening of the NPT is a third point. The NPT has been under review every 5 years at a review conference, the latest being in 1990, and in 1995, when the treaty expires, a conference will be held to decide whether the treaty should be extended. The NPT presently has a double role. Its primary goal has been the prevention of nuclear weapons proliferation. But, as an incentive for this, the treaty has also promoted the spread of civil nuclear technology for electricity generation. There is a conflict inherent in the spread of civil nuclear technology that indirectly increases the possibility of the spread of nuclear weapons. This conflict should be avoided and, with the decreasing importance of the role of nuclear energy on the international energy arena, it may be possible, at least in the long run, to make the NPT a treaty solely prohibiting the acquisition of nuclear explosives. This possibility could be addressed at the 1995 renewal conference. However, it may, by persons accustomed to the present nuclear world order, be considered a little too early for such a discussion to take place and we will probably, in 1995, see an effort to just renew the treaty, as it is phrased today, in order not to risk that the treaty is not renewed at all.

Fourth, a similar change in roles has to be made for the IAEA. The IAEA is today a strong promoter of the spread of civil nuclear energy, and is so as a United Nations (UN) agency. As the relevance of this work decreases, the IAEA can be made to concentrate on carrying out safeguards and on reactor safety issues. Developments in the world show that these tasks are more important than ever. It may also be the proper time for the UN to establish a new agency that can help to introduce efficient and sustainable energy technologies, especially in the developing world.

Of relevance when we are discussing a changing role for the IAEA is a fifth possible development. As the fissile material is removed from the nuclear weapons that are dismantled as a result of nuclear disarmament, the possibility of putting this material under international control should be carefully examined. It is possible that the IAEA can play an important role here. The agency could also play a role in co-ordinating the eventual reuse of the military fissile material in the civil nuclear fuel cycle.

Sixth, the handling of the final disposal of the military and civil fissile material from dismantled nuclear weapons and from civil nuclear electricity production has to be co-ordinated internationally. Whereas the long-term environmental concern of the handling of the waste may be of a local or perhaps regional concern, the long-term nuclear explosives predicament is global in its scope and needs a global approach in order for it to be resolved. This is discussed in a little greater detail in the concluding

⁶. There is an abundance of literature on this subject. A good book for a starter is Goldblat & Cox (1988).

chapter.

Before we discuss verification technologies in the next section, a few words should be said about on-site inspections. The present safeguards regime relies heavily on on-site inspections, and the NPT was for long the only arms control treaty of importance that depended on on-site inspections as a verification tool⁷. The great distrust between the United States and former Soviet Union made such inspections impossible for treaty verification until the late 1980's when the Document from the Stockholm Conference within the framework of the Conference on Security and Co-operation in Europe (CSCE) was negotiated, followed by the INF treaty on land-based intermediate- and short-range nuclear forces in Europe, the Vienna CSCE accords, the CFE treaty on reducing conventional forces in Europe and the START treaty on strategic nuclear arms reductions. These accords and treaties all have on-site inspections as an important verification method⁸.

In fact, the use of on-site inspections is the most important verification tool that can be used. If on-site inspections are allowed, technical means of verification are mostly helpful in making possible the triggering of such inspections and in simplifying the inspections. If only there were unlimited resources available for carrying out constant on-site inspections, technical means of verification would not be needed. In reality, however, this is of course not the case, and technical means of verification do play an important role and will also do so in the future.

Can a nuclear-weapons-free world be accomplished? It is difficult to answer this question with a yes or no with regards to feasibility, but it is of course not an impossibility in theory. We can ask ourselves whether a world that is only almost nuclear-weapons-free would be stable, and the answer is that this is doubtful. The existence of a few nuclear weapons in a post-nuclear world, albeit under international control, would put enough focus on these to cause an increase in the risk for proliferation.

While we are contemplating the possible existence of a nuclear-weapons-free world we can consider the feasibility of arriving at such a situation through international treaties and if it is reasonable to believe that such treaties could be verified by safeguards. It is then interesting to see that we are presently seeing the creation of a treaty that will achieve a comparable feat, the Chemical Weapons Treaty (CWT). This treaty is expected to ban all production and stockpiling of chemical weapons in the world. The verification problems are very similar to those concerning nuclear technology in that both are dual-use technologies. It is expected that the verification of the CWT will rely heavily on on-site inspections.

⁷. To be more accurate, the Antarctic Treaty from 1959, the Outer Space Treaty from 1967, the Sea-Bed Treaty from 1971 and the Agreement on the Moon and Other Celestial Bodies from 1979 allow on-site inspections.

⁸. The role of on-site inspections for verification of recently negotiated arms control and disarmament treaties have been discussed by Dunn & Gordon (1990) and Grier (1991).

9.3 Increased Future Use of “New” Verification Technology

As a post-nuclear world develops in our scenario and the long-term nuclear explosives predicament is resolved, the international safeguards regime develops from a system relying upon materials accountancy, with containment and surveillance as complementary methods, to one that emphasizes the detection of facilities that need to be inspected in order to ascertain that they are not used in a covert nuclear explosives programme. Such a safeguards system relies heavily on surveillance technology and on technology that simplifies the on-site inspections triggered by such surveillance.

We will in this section discuss two types of surveillance technology that would be advantageous to use in a post-nuclear world and one technology that could be developed for use during on-site inspections⁹. The first two are international satellite surveillance and international radionuclide monitoring and the third is remote, but close-by, detection of nuclear explosives or fissile material.

9.3.1 *International Satellite Surveillance*¹⁰

Since the early 1960's the United States and the former Soviet Union have had a monopoly on highly detailed surveillance information gathered from satellites in orbits around the Earth. The information available from these satellites created a situation of “open skies” between the superpowers during the cold war, and insight into the other side's military activities facilitated the verification of arms control and disarmament treaties and was beneficial to crisis stability. While there were confidence-building advantages in this situation there were also drawbacks to the monopoly. Outside parties could not verify one superpower's accusations of the other side's military superiority. Such accusations in many cases fuelled the arms race. This led to calls for international satellite surveillance to allow increased insight into the military affairs of the superpowers. Efforts to realize such ideas were made from the late 1970's until approximately the end of the cold war, both within the United Nations (UN) system and within individual countries¹¹. The role of the UN as an

⁹. Other technologies that one would think could be of importance in a post-nuclear world are the seismic detection of underground nuclear tests (see, for example, Goldblat & Cox 1988) or the optical detection of atmospheric nuclear tests (see, for example, Argo 1986). However, any safeguards regime existing in a post-nuclear world would need to detect a covert nuclear explosives programme long before a nuclear explosive were tested. The technologies involved should however be documented in order to allow the re-establishment of such verification technologies, should the stability of a post-nuclear world system be threatened.

¹⁰. This short section is based on a report written by the author (Swahn 1989). In the report the military satellite surveillance systems of the superpowers are described, the proposals for and the feasibility of international satellite surveillance are described and discussed, and the possible resolution limits for satellite surveillance are examined. Other documents of general interest for this subject are Swahn (1986B), Dorn (1987), Jasani & Larsson (1987), Jasani & Sakata (1987), OTA(1987) Ries & Skorve (1987), Florini (1988), Jasani & Larsson (1988), Swahn (1988B), Kokoski (1990B), Skorve (1990), and Krepon et al. (1990).

¹¹. Important early work on international surveillance by satellite was initiated within the Pugwash movement and in 1980 and 1982 two Pugwash symposia were held on the subject (Chayes, Epstein &

agency for international verification was examined, within the organization, in the late 1980's (United Nations 1991). The interest for international satellite surveillance within the UN increased considerably after the Kuwait crisis when the importance of satellite imagery for the support of the Allied forces became evident. At the same time the staff of the UN Secretary General were struck by the realization that the existence of timely information about the developing crisis would have facilitated the intervention of the UN early in the crisis without having to wait for the United States to take control of the events.

Military visible-light¹² imaging surveillance satellites of the United States and former Soviet Union have a close-look ground resolution of 10-30 cm¹³. If the optical systems could be made large enough, even better ground resolution could in theory be obtained. The ground resolution is, however, limited by atmospheric disturbances. Turbulence in the atmosphere limits the best possible ground resolution available from space to approximately 10-20 cm¹⁴. Modern United States imaging surveillance satellites, operating jointly with data relay satellites, have the capability to send images with high resolution in "live broadcasts" to ground stations on the other side of the globe¹⁵.

Until recently, few military satellite surveillance photographs had been published in the open literature. In August 1984, however, a British defence journal published three KH-11 satellite photographs that had been leaked from the United States Department of Defense (*Jane's Defence Weekly* 1984). The images show a ship being built at a former Soviet Union Black Sea shipyard. One of these is reproduced in Figure 9.1. The photograph has probably been processed to enhance edges and contrast. Even though the photograph has lost some detail in print, and is only a copy of perhaps many copies down the line from the original, an idea of the

Taylor 1977, *Pugwash Newsletter* 1980 & *Pugwash Newsletter* 1983). The ideas reached the international political arena in the late 1970's. On May 25, 1978, in an address at the 10th special session of the United Nations' General Assembly (the first special session devoted to disarmament), President Giscard d'Estaing of France proposed the establishment of an International Satellite Monitoring Agency (ISMA). As a consequence of this proposal, a UN study was made of the subject (United Nations 1981). On the individual country level the Canadian Paksat and the Swedish Tellus proposals for independent satellite surveillance systems have been the most elaborate (Canadian Department of External Affairs 1987, Swedish Space Corporation 1988).

¹². Visible light imaging is only one possible type of sensor system. Infra-red sensors and radar systems are also used for military satellite surveillance.

¹³. The ground resolution is defined as the size of the smallest detectable object on the ground. It is dependent on contrast and on the geometric form of the object. In this case the ground resolution is defined at a "normal" contrast ratio of approx. 2.5:1 and for round or square objects.

That a ground resolution of 10-30 cm for a surveillance satellite is relatively easily achievable can be demonstrated in quite simple calculations. See, for example, Swahn (1989, Appendix C).

¹⁴. Swahn (1989, Appendix D). It is possible to overcome the effects of atmospheric distortion by the use of adaptive optics. This technology is now commonly used when looking from the ground out into space, but it is uncertain whether the technology has, so far, been used when viewing the Earth from space.

¹⁵. Because most of the data are processed in Washington DC, this capability is important. However, during the Kuwait crisis and war it became evident that it was also necessary to be able to provide local military commanders with up-to-date images and a system was set up to allow the United States forces in Saudi Arabia to receive images directly from the imaging surveillance satellites as they passed overhead (Starr 1991).

detailed views from space that can be obtained by military imaging surveillance is given. The ground resolution can be estimated to be about 30-50 cm¹⁶.

Since the early 1970's civil remote sensing satellites have been launched and are presently operated by several countries and organizations. If one compares the ground resolution mentioned above with those of civilian remote sensing satellites there is a very large difference. The French SPOT satellite has a ground resolution of 20 m in the panchromatic (black and white) band and represents the best available digital images available today^{17,18}. A SPOT satellite image of Stockholm is shown in figure 9.2. As can be seen, streets and buildings are easily identifiable.

The smallest objects that can be seen on the best of present-day remote sensing pictures are thus approximately a factor of 100 larger than in the best military pictures. Pictures from the present generation of remote sensing satellites do therefore not have a large military surveillance value¹⁹. Harbours and airfields can be identified. Ships can be detected but not classified, with the exception of very large ships with a distinct shape, such as aircraft carriers. Smaller aircraft on an airfield or trucks on a road can not be seen in a SPOT image²⁰.

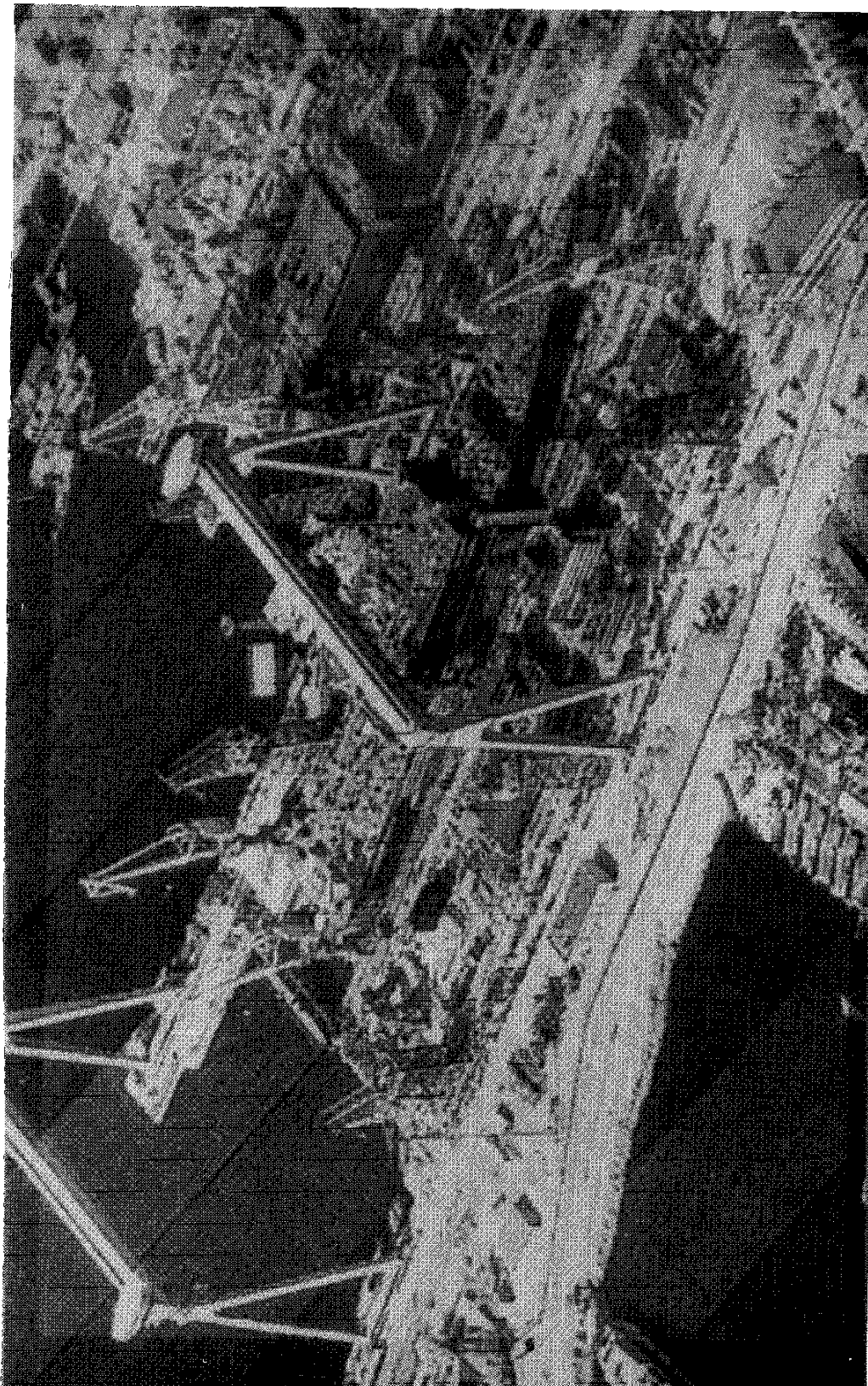
¹⁶. The KH-11 was the previous generation of United States military visible-light imaging surveillance satellites. It was the first type that allowed the taking of relatively high resolution images without using film. The use of film-based surveillance satellites was not discontinued until the latest generation of visible-light imaging satellites were introduced, the KH-12. The KH-11 did not reach a resolution of 10-30 cm. Therefore, the image in figure 9.1 is not the best that can be achieved from space.

¹⁷. The resolution of the SPOT satellite is often quoted as being 10 m, i.e., its instantaneous field of view (IFOV). The IFOV is the size of a piece of ground on the Earth's surface that one picture element (pixel) in the sensor on the satellite picks up light from. A geometric analysis, and general agreement by image analysts show that approximately 2 pixels are required to present the same amount of ground information as one line pair at a "normal" contrast ratio of approx. 2.5:1. This means that the IFOV resolution can be multiplied by 2 to get a value for the ground resolution of the panchromatic band of the SPOT satellite of 20 m.

¹⁸. The former USSR sells photographic images from its remote sensing programme on the international market via a company named Soyuzkarta. These photographic products have been advertised to have a 5-10 m resolution, but the actual ground resolution of the images has been found by Western photoanalysts to be about half this value, i.e., 10-20 m (Zimmerman 1990, Vance & Bumbera 1990, Reborchick, Cox & Biache 1990). It is possible that this discrepancy can be explained in the same way that the SPOT IFOV and ground resolution varies with a factor of two. However, the Soyuzkarta imagery has been produced by film-based systems and not via electro-optical systems. It is not natural to give the resolution of a film-based system as the IFOV, but rather as the number of line-pairs per mm that are resolvable in the photographic film. Approximately one line-pair is necessary to detect an object in a photograph and the ground resolution of a photographic film is often given as the distance on the ground that one line-pair represents.

¹⁹. Military intelligence communities in many countries are, however, realizing that satellite imagery can be had for sums that are not too prohibitive and that they may provide some information of relevance for military planning. That this is the case was well exemplified during the Kuwait crisis when the sales of SPOT imagery over the crisis area was stopped from the start of the crisis in August 1990 until March 22, 1991 (deSelding & Lawler 1990, Space News 1991).

²⁰. Larger aircraft, the size of a civil airliner, can however be detected. With a high contrast it should also be possible to detect a single large white truck on a black tarmac parking lot. One could not, however, see the difference between the truck and a white shed of the same size.



Source: Jane's Defence Weekly

Figure 9.1. United States military surveillance satellite image of a Black Sea shipyard



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Figure 9.2. SPOT panchromatic image of Stockholm

The ground resolution as defined in note 13 is based on objects that are approximately as long as they are wide. If an object is much longer than it is wide it can be detected even though its width is much smaller than the above given ground resolution capabilities of different satellite systems. This means that antennas and thick wires, for example high voltage cables, can be seen with the best military systems, and that railroads and roads, and even small paths across fields, can be seen in pictures taken by the SPOT satellite.

The ground resolution needed to detect an object is also dependent on the contrast. We have discussed the ground resolution for "normal" contrast. It is easier to detect high contrast targets (trucks in the desert or on snow fields, or ships at sea) than low contrast objects.

It is important to realize that the ground resolution of pictures from a surveillance satellite also depends on the orbital height of the satellite. A satellite working in a low orbit has a better ground resolution than it would have if the same satellite had been in a higher orbit. If the orbit of the SPOT remote sensing satellite was changed from its normal 830 km to 200 km, the ground resolution would be improved from 20 m to about 7 m²¹.

While the information content in the civil pictures is limited, there is presently an increasing interest in the news media for the use of remote sensing satellite pictures to illustrate coverage of military-related news stories. Academic researchers are using remote sensing satellite pictures for analysis of military activities. These uses will make pictures taken from space more familiar to political leaders and to the general public. As the opportunities of satellite surveillance are more widely demonstrated, the idea of a system of international surveillance satellites will have an increased chance of being realized²².

Satellite surveillance technology with very high resolution can in the future be used by an international safeguards body. If the long-term nuclear explosives predicament is resolved in the future, only the prevention of production of new militarily usable fissile material will be required. As was discussed in Chapter 2, the production of new militarily usable fissile material always relies on mined natural uranium as a raw material. Such mining is today extensive, relying on the upheaval of large masses of ore. This will be even more true in the future, as the richest and most easily retrievable ores are being utilized during the nuclear era. In a sustainable world, mining as a human activity has to be a relatively limited activity as the recycling of finite resources will be carried out as far as possible. Moreover, due to the environmental risks, it is probably carefully regulated and monitored. This means that a large-scale uranium mining effort should be relatively easy to detect as would other large-scale new constructions. The heat output of plutonium production reactors would also be relatively simple to detect by surveillance satellites, an example of which is shown in the case study at the end of this chapter.

²¹. 200 km is a low altitude for a military surveillance satellite, that would normally operate at an altitude on about 275 km and momentarily dip down to lower altitudes in order to obtain images of higher resolution.

²². An interesting development will also be the launching of a system of French military surveillance satellites, named Helios, beginning in 1993.

A system of international surveillance satellites would thus give important information to an international safeguards agency and could be used to optimize the effectiveness of on-site inspections.

9.3.2 *International Radionuclide Monitoring*

In a post-nuclear world, the background radiation levels of many short-lived but common isotopes produced in today's civil and military nuclear establishments would be much lower. The radiation from specific isotopes can be measured in very low concentrations. A reprocessing plant or an operating nuclear reactor under normal operations release small, but easily detectable amounts of different radionuclides. These can be detected at a distance as they are carried away by winds or ocean currents. For example, it is possible to find traces of the release of radioactivity from the British Sellafield reprocessing plant on the Swedish West Coast.

There are already an abundance of radiation monitoring stations, many of them automated, around the world²³. Today they monitor radiation release from nuclear accidents, nuclear weapons tests, etc. After the Chernobyl accident many countries, among them Sweden, improved their system of radiation monitoring systems. In a post-nuclear world such stations could play an important role as a safeguards instrument. A global interconnected chain of monitoring stations, on land, in the air and at sea could play an important role in an international safeguards regime operating in a post-nuclear world.

9.3.3 *International Systems for Detecting Nuclear Weapons and Fissile Materials*

There are already today a number of systems developed for detecting nuclear explosives or the existence of fissile material. First, the United States and the former Soviet Union have developed detectors that have been possible to use for detection of nuclear explosives on ships²⁴. Second, independent scientists have been doing similar work in an effort to show that it would be possible to verify a ban on nuclear weapons at sea²⁵. Third, some equipment of this type has been developed for safeguard use, mainly for non-destructive measurements of the isotope composition of fissile material²⁶. Fourth, there have been systems developed to aid units that have been set up to detect nuclear explosives in the event of a threat of nuclear

²³ The Swedish system is described by Vintersved & De Geer (1982) and Vintersved et al. (1987).

²⁴ As an example, a Soviet military helicopter-based neutron detection system for the detection of nuclear warheads on United States naval vessels is described in Belyaev et al. (1990).

²⁵ See, for example, Belyaev et al. (1990), Fetter & Cochran et al. (1990A), Fetter & Cochran et al. (1990B), Fetter & Frolov et al. (1990), Fetter & von Hippel (1990), Fetter, Prilutsky & Rodionov (1990), DeGeer (1990) and Sagdeev, Prilutsky & Frolov (1990).

²⁶ See, for example, Keepin (1986).

terrorism²⁷.

All these systems use similar types of detectors. These can be semiconductor-based detectors with multichannel analyzers for identification and measurement of specific isotopes, large volume detectors that can detect slight variations in the radiation levels compared to background levels, neutron detectors that can detect the presence of neutron emitting isotopes, and methods that involve the active irradiation of materials with neutrons that may induce nuclear reactions, i.e., fission, that emit large amounts of easily detected radiation.

A future international safeguards agency that had as a task not only to carry out material accountancy, but also to verify a ban on the production of fissile material, could thus have access to a number of different sensor technologies to be used when carrying out on-site inspections.

9.4 Use of Remote Sensing Imagery for the Verification of Military Nuclear Activity: A Case Study

In this section we will show some preliminary results of a study of possibilities of using presently existing remote sensing satellite imagery for the study of military nuclear activities²⁸. A SPOT panchromatic scene and a Landsat TM scene (bands 2, 6 and 7) of the Savannah River Plant near Aiken in South Carolina in the United States were purchased from Satellitbild in Kiruna, Sweden. The images were processed on a Teragon image processing system and on an Apple Macintosh system. The Savannah River Plant is a United States military nuclear facility for the production of weapons-grade plutonium and tritium²⁹. The plant is well described in the literature and there is therefore much information to use as "ground truth" to compare the satellite images with (see, for example, Cochran et al. 1987A and Cochran et al. 1987B).

There were two main objects of the study. The first was to see how the release of hot cooling water from the plutonium and tritium production reactors on the site would appear in the Landsat TM thermal infrared band³⁰. The second was to see how much information would possible to gain from studying facilities using the relatively high resolution of the panchromatic band from the SPOT satellite. The resolution of the Landsat TM scenes are 30 m per pixel for bands 2 and 7 and 120 m per pixel for the thermal infrared band number 6. The resolution for the SPOT panchromatic band is 10 m per pixel³¹.

There are a variety of military nuclear facilities within the Savannah River

²⁷ One such unit is the United States Nuclear Emergency Search Team (NEST) (Gates 1987).

²⁸ A comprehensive report is under preparation.

²⁹ It was also the sole plant in the United States for heavy water production until 1982 when this facility was shut down.

³⁰ A similar study has been made of the Chernobyl accident (Sadowski & Covington 1987). Infra-red studies of the heat output of the Savannah River Plant using aerial photography have previously been done (See Jensen et al. (1983) and the image on p. 27 in von Hippel, Albright and Levi (1985)).

³¹ These are the IFOV values. See note 17 for a discussion of what ground resolution this represents.

Plant. Of main interest for our study were the four heavy-water moderated nuclear production reactors named P, L, K and C³². The reactors have a typical thermal power output of 2 150 MW_{th}, which is comparable to a small-sized civil electricity generating nuclear reactor³³.

The reactors are indicated in the map in figure 9.3 and in the overview using a SPOT panchromatic satellite image in figure 9.4. In addition the Vogtle civil nuclear power plant is shown³⁴.

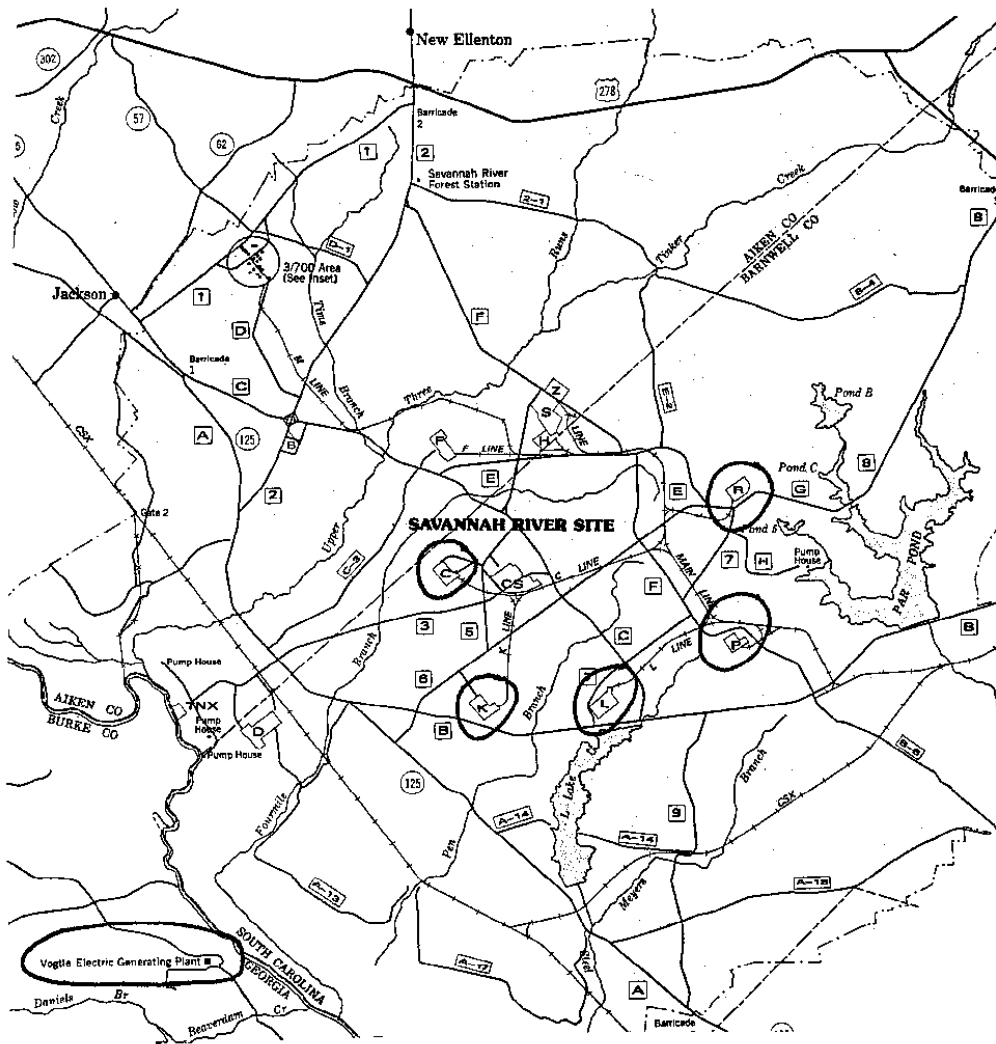
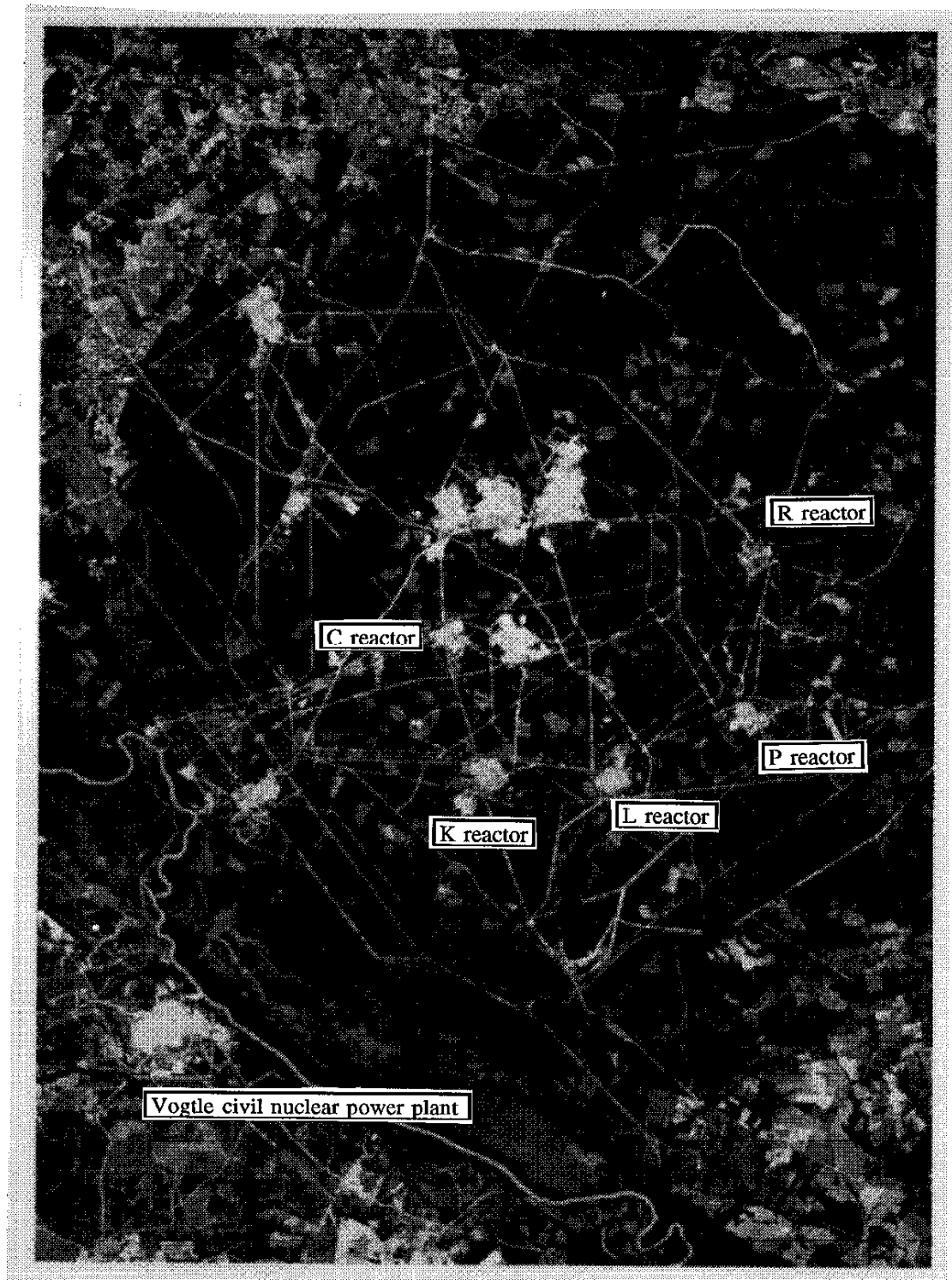


Figure 9.3. Map of the Savannah River Plant

³² There is also an R reactor which has been closed since 1964.

³³ At a 30% efficiency 2 150 MW_{th} would represent a 645 MW_e electricity generating nuclear power reactor.

³⁴ The first reactor at this plant was put into operation in 1987 and therefore the thermal plume from this reactor could not be detected in our study, as the Landsat image was from 1984.



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Figure 9.4. SPOT satellite image of the Savannah River Plant

Due to operating safety reasons, the reactors at the Savannah River Plant were shut down during the late 1980's and have so far not been restarted. We therefore had to go back somewhat in time in order to find a good date for the Landsat TM scene as we wanted to be as certain as possible that several reactors were operating. In addition, as Landsat 4 was launched on July 16, 1982 and Landsat 5 on March 1st 1984, the thermal infrared data has to be from after these dates. A listing of the operating history of the reactors from 1982 to 1988 was located³⁵. December 1984 was chosen as a good month for acquiring an image and a cloud-free image of the area from December 15th, 1984 was purchased. The SPOT panchromatic image was then to be chosen, and a decision was taken to purchase a more recent image, i.e., from October 16, 1990³⁶.

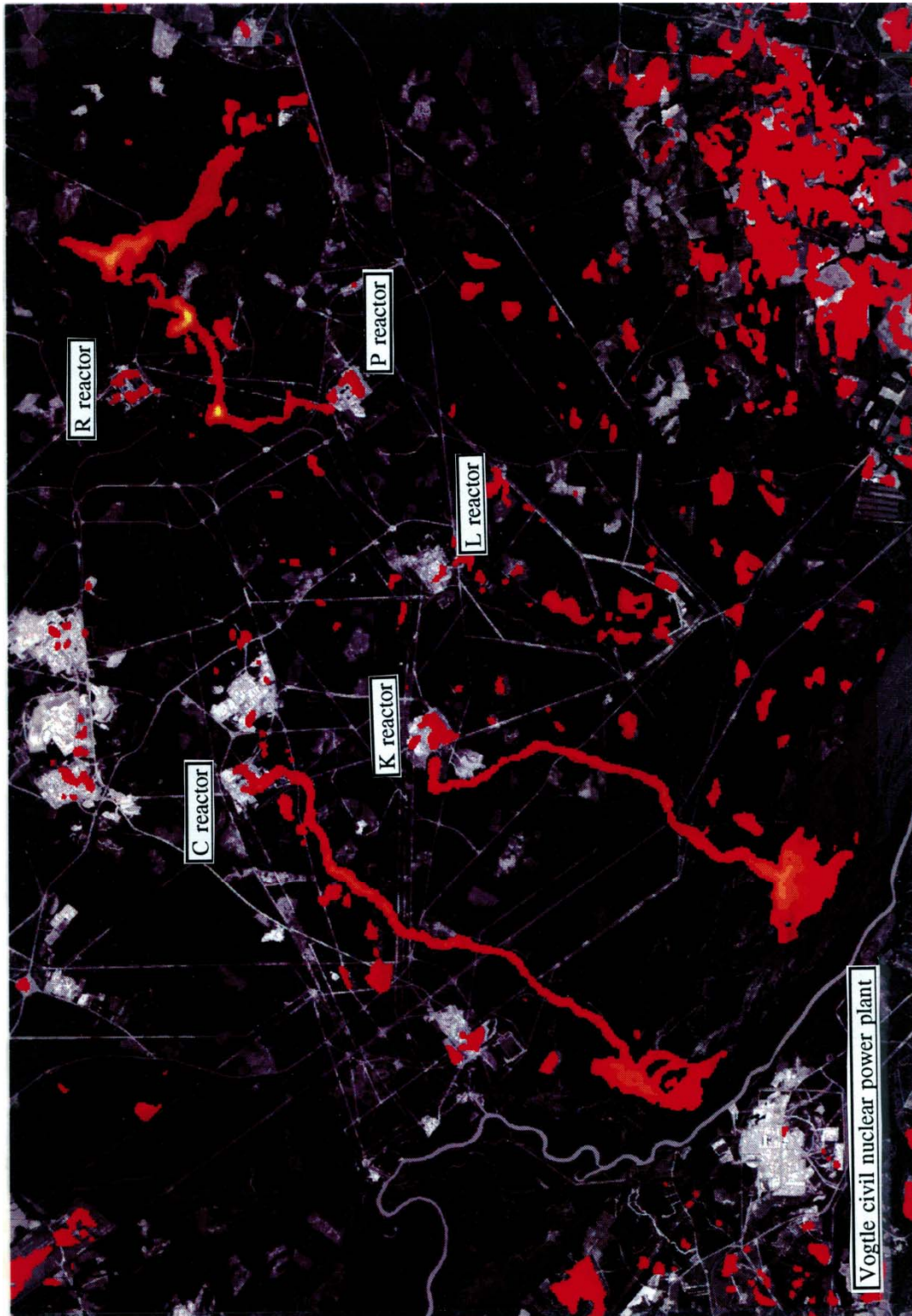
We wanted to use the Landsat TM6 thermal infrared band to register the heat output from the cooling of nuclear reactors. When combined with panchromatic image from the SPOT satellite the heat output can be connected to the reactors which are easily visible in the SPOT image³⁷. An image showing this is presented in figure 9.5. In the figure the heat output from the three reactors P, K and C is presented in colour, where yellow denotes a higher pixel value and thereby a higher temperature. The P reactor in the upper right corner releases its cooling water into a reservoir and the C and K reactors release their cooling water into the swamps on the northern side of the Savannah River.

The thermal output from the operating reactors is thus easily detected. However, there are several features in the image that are due to the relatively poor 120 m per pixel resolution in the thermal information. One would expect the temperature to be highest close to the reactor and then to fall as the water cools as it flows away and mixes with cooler water in the reservoir and swamps, but this does, strangely enough, not seem to be the case in our figure. However, what one sees is the result of the averaging out of temperature readings that occur when a very narrow but hot stream runs through cooler surroundings. The 120 m pixel width averages in the surrounding temperature so that the stream appears much cooler. In fact, when we set the lower threshold for the information to be included in the thermal data we had to set it so low in order to get a well-connected heat output that some large areas away from the thermal output, heated by the sun on a December day with clear skies, had the same average temperature. What we also see is that when the hot water spreads out over a larger area, then it shows up as a hot spot.

³⁵. Personal communication with Thomas B. Cochran of the Natural Resources Defence Council, Washington DC.

³⁶. One reason for choosing a recent SPOT image was to be able to compare the Landsat TM band 2 and the SPOT image in order to investigate the possibility of discovering changes that had occurred between the two dates.

³⁷. The images that were purchased were geometrically corrected to level 2B by Satellitbild in order to make the superposition of the images more accurate. US Geologic Survey 1:24 000 maps supplied by the author were used to do this correction.



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Figure 9.5. Thermal output from the production reactors

It is also interesting to see how much detail could be seen in the SPOT panchromatic image. Figure 9.6 shows the L reactor in a close-up view and figure 9.7 shows an aerial photograph of the reactor. No detailed analysis is carried out here, but there is a large amount of information available in the image. A forthcoming report will discuss this issue further.



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Figure 9.6. Close-up SPOT panchromatic image of the L reactor.

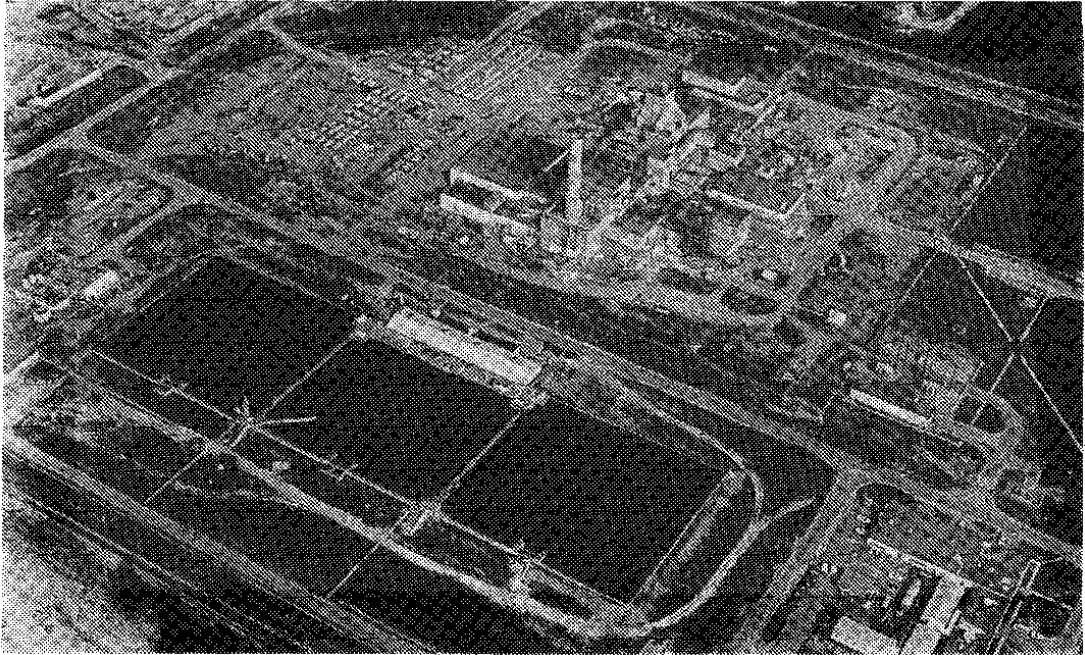


Figure 9.7. Aerial photograph of the L reactor (from Cochran et. al. (1987B, p. 97))

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10. CONCLUSIONS

The time has come to sum up the most important points that have been covered in the thesis and to see what conclusions can be drawn from the discussion. We have found that the long-term nuclear explosives predicament exists only if the recycling of plutonium in a long-term and large-scale plutonium economy is not carried out. Because of limitations in natural uranium supplies, in the long term, such an economy would have to rely on fast breeder reactors. All the reactor-grade plutonium produced in today's nuclear reactors as well as fissile material from a nuclear disarmament, in this case probably less likely, would be consumed in the long run. On the other hand, large amounts of weapons-grade plutonium would circulate in such a society.

At the present moment, however, there are indications that a plutonium economy will never develop. Strong arguments can be put forward why it should not be developed, even if in the future it would become close to being economical compared to renewable and sustainable energy sources. First, a large-scale nuclear-based world would not be ecologically sustainable, since it would not belong in a world where societal handling of natural resources is designed to fit into the energy flows and material cycles of nature. Second, the nuclear proliferation problems in such a world would be very large. A post-nuclear world using sustainable and renewable energy sources is thus the only long-term alternative to a large-scale plutonium-based nuclear world. In the long run there is no third way out¹.

One problem with the present solutions for the long-term disposal of high-level radioactive waste is that they are based on the planning that was common when it was prevalently thought that all spent fuel was to be reprocessed. In this case, no fissile material was ever to be disposed of in the repositories, but would be recycled. There would then only be a long-term radiological problem that was thought to be solved by, for example, the Swedish KBS-1 method.

When the hopes for an immediate and large-scale development of a plutonium economy were shattered by near-term economic and proliferation realities, it was decided in many countries that direct disposal of the spent fuel was to be carried out. As a result of this, the KBS-3 plan for final disposal of spent fuel was developed in Sweden. This plan was only a slightly modified version of the KBS-1 plan in order to take into account the change in long-term radiological situation that would persist in the spent fuel compared to the reprocessing high-level nuclear waste. It appears as though very little thought was put into examining the difference between depositing the plutonium in repository and not doing so.

In the review part of the thesis we examined the possibilities of constructing a nuclear explosive using reactor-grade plutonium. We found that such plutonium is possible to use for this purpose, although if weapons-grade material were available it would be more efficient to use this material instead. We also found that if laser isotope separation technology is available, it is possible to convert reactor-grade

¹. For a discussion of the future of fusion energy as a third alternative, see note 32 in Chapter 1.

plutonium into weapons-grade plutonium.

In exploring the long-term nuclear explosives predicament we first developed a scenario for how much fissile material might be left to be disposed of in a post-nuclear world. We then found that the reactor-grade plutonium in the spent fuel would pose a proliferation threat up to 70 000 years into the future, as it is, and up to 250 000 years in the future, if isotope separation techniques are used to separate the ^{239}Pu from the remaining ^{242}Pu . We also found that such separation could be done with conventional isotope separation techniques. In addition, the reactor-grade plutonium can at all times be converted to weapons-grade plutonium using laser isotope separation techniques. We also found that some of the characteristics of the plutonium that are important from the viewpoint of nuclear explosives construction improves within a time-frame of 1 000 years and that the accessibility of the spent fuel, and thereby of plutonium, in a mined repository likewise improves.

When we then examined the possibility of removing safeguards from a final repository of spent fuel of the Swedish KBS-3 type, i.e., a mined repository at a depth in bedrock of approximately 500 m, we found that this will not be possible and that some sort of surveillance of the repository would be needed for an indefinite time. The fissile material in the spent fuel was found not to be “practicably irrecoverable”.

As discussed above, there are two possible energy futures, the first being a plutonium economy and the second a sustainable energy future based on renewable energy sources. The first provides a radiological long-term nuclear waste problem, i.e., reprocessing nuclear waste². Such waste would be produced continuously in a plutonium economy, and would need to be disposed of in repositories³. The second route would leave a large but finite nuclear waste handling problem to dispose of in a post-nuclear world. This waste would include large amounts of militarily usable fissile material. This means that the method for final disposal of high-level nuclear waste has to be chosen in such a way that it is either a long-term solution for the radiological environmental problem of reprocessed high-level waste or a solution to the long-term environmental and proliferation problem of spent fuel and military fissile material. The same solution can not necessarily be used for the two different energy futures⁴.

We also tried to find solutions to the long-term nuclear explosives predicament, i.e., solutions that allow practicably irrecoverable disposal of the spent fuel and military fissile material. We found that there are some possible candidates for such solutions. However, when one weighed together technical feasibility, environmental

². As we saw in Chapter 8, the amounts of waste and the longevity of them might be reduced by transmutation, although this would probably be found too expensive. There would still be the need for smaller repositories as the transmutation process would not be 100% effective.

³. Even if one could afford to reduce the amounts of reprocessing HLW by transmutation technology, there would always trickle out some waste out of the system that would need long-term and secure disposal.

⁴. A solution that solves the long-term nuclear explosives predicament and the long-term radiological problems of disposing of spent nuclear fuel would, however, also provide a satisfactory solution for disposal of civil and military high-level reprocessing wastes. This means that the reprocessing waste that already exists does not create a large additional problem.

impact, costs and public acceptance we found that the deep borehole method for disposal was the most promising.

We also briefly examined the question whether one should inform future generations of the whereabouts and contents of the repository. If one only has an environmental hazard as a concern, i.e., in a repository for reprocessing waste, to inform future generations is a reasonable objective, as it warns them of hazards. If one, however, has built a repository for spent fuel and military fissile material, one could argue that it would be better to “forget” the existence of the repository. Building up archives in vaults in an attempt to communicate with generations thousands of years in the future might not be a good idea. This also means that the environmental safety of such a repository would have to be very high and the risk for unintentional penetration into the repository would have to be minimal.

We can here return to the ethical standpoint that we should not restrict the possibility of future generations to take responsibility for their own active actions. This is a very reasonable standpoint in general, but it might be questioned in relation to the nuclear explosives predicament. A repository of high-level reprocessing waste will have mainly local or regional effects on the environment if subject to intrusion in the future. A repository of spent fuel can, on the other hand, easily have global proliferation effects. To argue that future generations should be allowed to take responsibility for their own active actions is very questionable when a possible outcome of these actions is that millions of innocent individuals in that generation might be killed in the holocaust of an accidental nuclear war. Our generation has experienced and survived such a threat. In my opinion, it is part of our generations responsibility to bring down the risk of such a future nuclear proliferation to as low a level as possible. This might be done by the choice of a proper disposal method in combination with an effort not to inform.

Here we touch upon another problem that makes the solution of the disposal of spent fuel and the long-term nuclear explosives predicament different from solutions of the disposal of reprocessed high-level nuclear waste. All the existing spent fuel and military fissile material has to be disposed of in a way that is practicably irrecoverable. If one country puts a lot of effort into such a disposal and another country does not, then the value of the first country’s efforts is diminished. The future generations living in the first country may well be effected by proliferation problems in the second country. This points to the need of an internationalization of the nuclear waste handling system for spent nuclear fuel and for military fissile material. The role of the United Nations and IAEA is here vital⁵.

We do have time to wait for a few decades to see in which directions the global energy system develops, and what the role for nuclear power will be in it, before final decisions need to be taken on the final disposal method of nuclear waste. Funding for disposal, however, has to be secured now. This is especially true if a post-nuclear world is the energy future that develops. If there is no future utilization

⁵. Unfortunately it may take some time before the IAEA will put this problem high on the agenda. That organization is strongly supporting a future plutonium-based economy and it may be difficult for it to make an unbiased evaluation of the future of nuclear power.

of nuclear power that can be taxed to pay for the waste handling of previous generation's nuclear power utilization, then a situation may prevail where we presently use an energy form with very large waste handling costs without those costs being borne by the users⁶.

The need for proper economic evaluation of nuclear power and of the economic planning for future nuclear waste disposal has to be stressed. It is important that all costs are included when the choice of technology for future energy use has to be taken. Some costs for research and development of new energy systems have to be subsidised – as they have always been – but once the technology is mature enough to compete on a market it should do so on its own terms. Sunk costs for fuel fabrication or costs for environmental pollution and waste handling should not be ignored. Such costs are not easily integrated into present-day economic planning, but there are signs that a green economic accountancy will soon become much more important than it is today. This means that the costs for waste disposal, for the dismantling of old reactors and reprocessing plants as well as the costs for cleaning up the scars caused by uranium mining should be included in the present costs for the use of nuclear energy⁷.

The proper economic evaluation of different energy forms is very important in another aspect. The final choice between a long-term plutonium-based economy and a post-nuclear world with energy use based on sustainable and renewable energy sources will probably take place within the next fifty years, as the costs of using fossil fuels begin to rise⁸. The abundant availability of and use of fossil fuels today, without charging the use of these fuels with their environmental costs, makes the energy markets difficult both for nuclear energy and for renewable energy sources.

This also has relevance when one decides how the weapons-grade uranium and plutonium from dismantled nuclear weapons are to be handled in the future. If these materials are to be recycled into the civil nuclear fuel cycle, it is important that they do not provide subsidies for nuclear energy to the disadvantage of other energy sources. This does not mean to say that such recycling should not take place in order to reduce the final waste handling problem, but it would be cynical if the process of nuclear disarmament today led to a future world where proliferation would become a day-to-day problem even larger than today.

The issues discussed in this thesis are global, and we have said that in many ways Sweden has been a forerunner in the way the nuclear waste handling problems have been handled. We have considered the Swedish KBS-3 method and the Swedish system for the handling of spent nuclear fuel as a reference method. What are the implications of the conclusions arrived at for this reference method? First, we have found that the KBS-3 method does not satisfy the criteria for “practicable

⁶. In Chapter 4 we studied the Swedish system for funding of nuclear waste handling and found it to be ambitious, but there were still clouds on the horizon.

⁷. Another cost that nuclear power does not pay are the insurance fees for coverage for full liability against the effects of nuclear accidents. Liability is now strongly limited and the utilities do not have to compensate costs above a certain amount.

⁸. It is of course possible that one will internationally decide to curb the use of fossil fuels, and then the choice has to be taken earlier.

irrecoverability” needed to avoid indefinite safeguard arrangements for the repository. This does mean that the KBS-3 method should, in principle, be abandoned. As we have seen earlier, the company responsible for the handling of the Swedish nuclear waste, SKB, has already done some research on the “deep boreholes” method of disposal. This work should be intensified, with the goal of finding a practicably irrecoverable disposal method for spent nuclear fuel.

Regarding the question of “forgetting” where the repository is situated, this would mean a turn-around of Swedish planning that now tries to find methods for passing on information about the repository to future generations. This means that there is much research to be done on this new issue.

In line with what we have said above, it is important that Sweden looks for possibilities of establishing international co-operation in an effort to find a disposal method that allows “practicably irrecoverable” disposal of spent nuclear fuel.

The existence of the long-term nuclear explosives predicament also influences the Swedish system for funding the handling of nuclear waste. As it is necessary to change method for final disposal of spent nuclear fuel, it may be found more costly to dispose of the spent fuel than previously calculated. New calculations have to be made that allow good margins for cost increases and new fee levels have to be established for the electricity generation using nuclear power.

There is another problem concerning funding of nuclear waste disposal that effects the possibility to avoid passing on economic costs to future generations that establish a post-nuclear and sustainable world. The Swedish system for funding the final disposal of spent nuclear fuel is dependent on a real interest of 2.5% on the deposited funds. Real interest is at least indirectly dependent on economic growth of about the same size. A sustainable world could not allow such growth unless it is tied to a development disconnected from the large-scale handling of energy and materials of today’s industrial countries. There might thus be a conflict between this system of funding and the development of a post-nuclear world.

Let us now return to a text we cited, albeit in a footnote, in the introductory chapter. We there cited a document, that came to the following conclusion⁹:

“The analysis that has been done regarding the possibility that the final repository for spent fuel might become a “plutonium mine” shows that a country that wants to gain access to Pu-239 for nuclear weapons chooses other methods for this, primarily the short-time irradiation of uranium in a nuclear reactor.”

We also wrote that this statement could be called a “common view” shared by most people who work with, and plan for, the disposal of high-level nuclear waste.

First, however, we want to repeat that this comment, when used in the present tense, is also accepted by the author of this thesis. He is, however, certain that he,

⁹. We can now describe this document in a little more detail. It is Appendix 9 of the first annual KASAM (The Consultative Committee for Nuclear Waste Management [Samrådsnämnden för kärnavfallsfrågor]) report on “The State of Knowledge on the Nuclear Waste Front” (KASAM 1986, pp. 128-9). The appendix is called “Plutonium i använt kärnbränsle [Plutonium in Spent Fuel]” and is based on a memorandum from the Swedish National Defence Research Institute [Försvarets forskningsanstalt] (Strömberg 1986).

and many others with him, would have been very concerned if such a repository, that had been constructed and filled with spent nuclear fuel 1 000 years earlier, would have existed 200 km west of Baghdad in Iraq in the autumn of 1990. With relatively little effort, the Iraqis could have gained access to fissile material for nuclear explosives within a relatively short time.

Today this scenario is not yet valid. We have not even built our first repositories. But, this is the type of scenario that could develop time after time during the whole period that the spent fuel repository has to function. We are, after all, discussing time-spans on the order of hundreds of thousands of years.

We would also like to return to the first document cited in the beginning of the introduction. It also states¹⁰:

“The principle concerning the limitation of the burdens on future generations also implies that they need not take any action to protect themselves against effects of waste disposal. Thus, such disposal alternatives, which rely on monitoring, surveillance or other institutional controls as a primary radiation protection feature for very long periods of time, are not recommended. This is because institutional controls are not considered very reliable beyond a few hundred years and they would represent a significant burden upon future generations.”

This statement concerns radiation protection, the main interest of the report. When compared to the statement in the same report that was cited in Chapter 1, i.e., that the “final decision on the need for safeguards surveillance should be made by the generations living during the closure of the repository and thereafter”, we find that the difference is striking. This is most certainly not at all intentional, but rather an effect of the general lack of interest in the safeguard problem within the civil nuclear establishment¹¹. Perhaps this thesis can help in putting the long-term nuclear explosives predicament on the agenda, together with the environmental problems, when discussing the final disposal of spent nuclear fuel. The two subjects might not merit equal attention, but the interest devoted to the safeguard aspects has so far been much too shallow.

The discussion of the ethics of the handling of long-lived nuclear waste ought to be continued, and the consequences of the long-term nuclear explosives predicament should be included in such discussions. The principle that burdens on future generations shall be avoided should be used also for this predicament, and not only for the environmental effects of the nuclear waste. The question of what such considerations should be allowed to cost can be debated, but the present way of perhaps adjusting the sums set aside for waste handling to what the economics of the nuclear power plants can carry, is not acceptable. If this is what is happening, and

¹⁰. Nordic Radiation Protection and Nuclear Safety Authorities (1992). Once again it should be mentioned that this document is still in draft form. See the reference list for a detailed description of the status of the document.

¹¹. This document is, however, a draft for a document to replace a previous version (Nordic Radiation Protection and Nuclear Safety Authorities 1989). The previous document only mentioned the proliferation aspect in the introduction. This means that more effort has been put into examining this question than in the previous document. Perhaps the contents of this thesis can be of further help.

this leads to the carrying through of a sub-optimal nuclear waste handling method, then it might even be better to transfer the waste to future generations without specifying what solution should be used^{12,13}. When making a choice of waste disposal method, and how much it should be allowed to cost, they would at least not have to take into deliberation such very short-term aspects. And, they might have a better ethical understanding of the need to prevent burdens to future generations, especially if we have left large burdens on them¹⁴.

Finally, let us not forget the main issue at stake. The energy use in the long-term future could be based on a plutonium economy and the final disposal of reprocessing waste will then need to be done in an environmentally acceptable way. A combination of the Swedish KBS-1 and KBS-3 methods is probably acceptable for such disposal. We may, however, see the development of a long-term sustainable energy future that will rely on renewable energy sources. Such a world would only be using nuclear technology on a small scale, i.e., it would be a post-nuclear world. If this is the energy future that develops, the spent fuel from the present use of nuclear power will have to be disposed of with the plutonium still present in the waste. Such fuel will have to be disposed of so that the long-term nuclear explosives predicament does not put a burden on future generations living in a post-nuclear world. Disposal solutions of the Swedish KBS-3 type do not fulfil this requirement.

Which energy future will be the one that develops? Which type of waste disposal method will be the one that needs to be developed? Perhaps we will see clearer signs of this a little into the next century. Until decisions have to be taken, however, there are two main efforts that can be made. First, one can try to promote that the planning for the final disposal of high-level nuclear waste is done with this uncertainty in mind, and that there is an international co-ordination in such planning. Second, one can make certain that once a decision can be taken there will be enough funds for realization of the waste disposal method chosen. The reservation of such funds, at realistic levels, has to be made in all cases where high-level nuclear waste is produced.

Thus, we are moving into an uncertain future. Taking decisions in the face of uncertainty has always been difficult. If this thesis can help to show the way forward to remove some of the uncertainties, then the struggle involved to produce this work will have been worthwhile.

¹². This does not mean that we should not set aside as much capital as possible for them to use, so that they do not have to pay for the disposal all on their own.

¹³. There is one aspect to this type of solution that might actually make it seem very attractive to some persons. If one is of the view that the fissile material in the spent fuel is to be, and will surely at one time or another be, used as an energy source then the costs of handling the waste after such use could be borne by the generations who decided to use it. This means that it would be possible to use a much cheaper solution as it need not be long-term, and that such a repository should not be sealed to allow easy retrieval of the "fuel".

¹⁴. Actually, we see some tendencies for such a change in ethical understanding already in today's world. We are now almost daily faced with new clean-up costs for previous environmental neglect. This does force us to look at how we are presently dealing with similar problems, and to take much more care, and pay much higher fees, than was previously the case, since the costs are easily underestimated.

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APPENDIX 1: USE OF TERMINOLOGY

In this appendix some of the ambiguities that exist concerning terminology within the field of the thesis are examined. Motivations are given for the terminology that have been chosen for use in the thesis. Two areas are examined. These are terms related to nuclear explosives and to nuclear waste.

Nuclear Explosives

In this thesis the term nuclear explosive is used when discussing a device that is constructed in order to utilize the explosive forces of nuclear fission or fusion reactions. A nuclear explosive can be put into a military system, it can be used as a terrorist device, it can be used for peaceful purposes or it can be constructed solely as part of a research and development project. This means that the term has a wider use than the often used term nuclear weapon which has a more narrow definition. Alternative terms that are sometimes used instead of nuclear explosive are nuclear device or nuclear explosive device.

A nuclear weapon is a nuclear explosive that is designed to be used in a military system. A nuclear weapon consists of a nuclear warhead (containing the nuclear explosive and triggering mechanisms) and some kind of packaging that allows the warhead to be used in a nuclear weapon system. This packaging can, for example, be a missile, a bomb shell-case, an artillery shell-case or a mine case. The nuclear weapon system, as a whole, also includes the weapons carrier and a command and control structure. The weapons carrier can, for example, be a missile launcher, fixed or mobile, i.e., a silo or a submarine, an aircraft that can drop bombs or an artillery gun. The term atomic weapon was used earlier instead of nuclear weapon.

Peaceful nuclear explosives (PNEs) are nuclear explosives designed, for example, to stimulate gas fields or for the excavation of canals. Much research was carried out within this field from the middle of the 1950's to the late 1970's¹. The former Soviet Union has exploded a number of PNEs for different purposes, the most common being to increase the output of oil and natural gas wells, geological research and the creation of underground cavities for storage.

The term gadget was, for reasons of secrecy, used of the first nuclear explosives that were constructed during the Manhattan Project². The use of the terms gadget and device was later common within the nuclear weapons laboratories³.

¹. See, for example, Teller et. al. (1968), IAEA (1970), IAEA (1971), IAEA (1974), IAEA (1975), IAEA (1978), Long (1975), Myrdal (1975), Wallin (1975) and O'Neill (1989).

². See, for example, Hansen (1988, p. 33). For descriptions of the early development of nuclear weapons refer to Smyth (1945), Jungk (1956), Lamont (1965), Brown & MacDonald (1977), Kunetka (1978) and Rhodes (1986).

³. See, for example, McPhee (1974, p. 115).

Nuclear Waste

Regarding the terminology that is used when discussing nuclear waste we here discuss two main topics. The first is what to call the different types of nuclear waste, and whether or not the fissile components of the nuclear warheads in nuclear weapons should be considered nuclear waste. The second is what the separate components of nuclear waste should be called.

Nuclear waste is commonly divided into three categories, depending on the levels of radioactivity, heat content and potential hazard of the waste. These categories are most often referred to as low-level nuclear waste, intermediate-level nuclear waste and high-level nuclear waste. In this thesis we only concern ourselves with discussions of high-level nuclear waste⁴.

High-level Civil and Military Nuclear Waste

IAEA, in its Radioactive Waste Management Glossary (IAEA 1988) defines high-level nuclear waste, hereafter referred to as HLW, as:

- ”(i) The highly radioactive liquid, containing mainly fission products, as well as some actinides, which is separated during chemical reprocessing of irradiated fuel (aqueous) waste from the first solvent extraction cycle and those waste streams combined with it.
- (ii) Spent reactor fuel, if it is declared a waste.
- (iii) Any other waste with a radioactivity level comparable to (i) or (ii).”

Zhu & Chan (1989, p. 6) in the IAEA Bulletin give the following simplified description and explanation of HLW:

”High-level wastes (HLW) arise from the reprocessing of spent fuel from nuclear power reactors through which uranium and plutonium can be recovered for re-use. These wastes contain transuranic elements, and fission products that are highly radioactive, heat generating, and long-lived. Liquid HLW has been effectively stored in tanks at specially constructed facilities. Before final disposal and isolation from the biosphere, they require treatment and solidification. Spent fuel that is not reprocessed may be considered a high-level waste.”

An important point can be made here. The term HLW was originally used only for the fission products and actinides resulting from reprocessing of spent fuel, i.e., the plutonium and uranium were not included. Because of the still prevailing idea,

⁴ IAEA, in its Radioactive Waste Management Glossary (IAEA 1988) defines low-level waste as

”Waste which, because of its low radionuclide content, does not require shielding during normal handling and transportation”

and intermediate-level waste (or medium-level waste) as

”Waste of a lower activity level and heat-output than high-level waste, but which still requires shielding during handling and transportation. The term is used generally to refer to all wastes not defined as either high-level or low-level.”

The definitions for major categories of radioactive wastes, as classified in the United States, can be found in Tsoulfanidis & Cochran (1991).

within relatively wide parts of the civil nuclear establishment on both national and international levels, that the uranium and plutonium in the spent fuel should (and will eventually) be recycled there is a big hesitation to classify spent fuel as HLW. In the literature this can lead to confusion as discussion of the properties of HLW sometimes only involves the waste under (i) above, sometimes only the waste under (ii) above, and sometimes involves a more comprehensive discussion. One should take care when comparing data that describes characteristics of "HLW".

The spent fuel can be from different types of reactors and of different degrees of burn-up; it can even be spent MOX-fuel. These differences only influence the long-term characteristics of the spent fuel in minor ways and there is no need for differentiating between different types of HLW because of these differences.

As the once-through fuel cycle is adopted as the preferred nuclear fuel cycle by an increasing number of countries, the term HLW will probably in the long run be used mainly for describing spent fuel and the numbering of (i) and (ii) in the IAEA classification will probably be reversed. This poses no problem. Any HLW from reprocessing, once it is vitrified, should not be more difficult to dispose of than spent fuel and therefore it is a natural sub-category of so defined HLW.

This argument is not reversible. If the term HLW is used to denote only waste from reprocessing, as was originally done, then the waste disposal solutions need not take into account the problems that the possibility of using reactor grade plutonium for the construction of nuclear explosives leads to, i.e., the long-term nuclear explosives predicament discussed in this thesis. Such waste disposal solutions can, without large changes, be transferred to deal also with spent nuclear fuel with regard to long-term radiotoxic problems. But, this should not be done without seriously re-evaluating the disposal solution concerning the long-term nuclear explosives predicament.

When the spent fuel from nuclear power reactors is reprocessed then, apart from HLW, there is also reactor-grade plutonium produced in pure form. This plutonium has gone into limited use as MOX-fuel and as fuel in experimental fast breeder reactors. Much of this is, however, presently stockpiled as the economics of recycling has proven to be questionable. Most of this reactor-grade plutonium may never be used in this way and, if it is to be disposed of as waste in the future, it will have to be considered to be HLW.

This statement leads us over to a discussion of the military production of HLW. The military production of weapons-grade plutonium is very similar to the civil process of running a nuclear reactor and reprocessing the spent fuel. The weapons-grade plutonium is separated from the spent fuel of military plutonium production reactors and the result is high-level reprocessing waste very similar to the civil high-level reprocessing waste. In the same way as reprocessed reactor-grade plutonium should be considered as HLW if it is never used in reactors, the weapons-grade plutonium from dismantled nuclear weapons can be seen as HLW if it is to be disposed of without any conversion.

When nuclear weapons are dismantled, weapons-grade (highly-enriched) uranium is also a waste product, which in the long-term future is usable in nuclear

explosives⁵. As is discussed in the thesis, some of this material may be used as civil nuclear reactor fuel, but in case it is not, it should be classified as HLW, not necessarily because of its radiotoxic characteristics, but because of the long-term possibility of using it for the construction of nuclear explosives.

There is also HLW produced in civil nuclear research reactors and military naval propulsion reactors. The waste is similar to that of other reactor HLW, but the plutonium content may be lower as they are sometimes fuelled with highly-enriched uranium.

Finally, for completeness, there is also a type of nuclear waste, both civil and military, that is called alpha-bearing waste (or transuranic waste⁶, or alpha waste). This is nuclear waste that could normally be handled like intermediate-level waste but because it has been contaminated with long-lived alpha-emitting isotopes it may need to be handled like HLW. This waste, although it may contain small amounts of uranium and plutonium, is of no significance when discussing the long-term nuclear explosives predicament of HLW and is therefore not considered in this thesis.

Components of High-level Nuclear Waste

The terminology used to describe the components of radioactive high-level nuclear waste (HLW) can be also confusing. The HLW can be said to consist of fission products, i.e., isotopes of relatively light and short-lived elements, and of isotopes of heavy, often long-lived, elements.

The nomenclature problems arise in the different ways of describing the heavy elements in the nuclear waste. Originally only uranium, in its natural form or enriched, is present in the nuclear fuel, usually as an oxide. When the reactor is operated new isotopes of heavy elements are formed (apart from the fission products). Because these elements have a higher atomic number than uranium they are sometimes called trans-uranium elements or trans-uranides. Also, because they all belong to the actinide series in the periodic table, i.e. are members of the 15 radioactive elements having increasing atomic numbers from actinium (89) to lawrencium (103), they are sometimes called actinides. These terms as such do not cause confusion, but when they are used in literature in discussions of HLW the words trans-uranides or actinides are often used only for the elements other than uranium or plutonium in the HLW. This means that tables and diagrams which describe a characteristic of "trans-uranides" or "actinides" in the HLW usually only refer to the actinides removed in reprocessing. This for long became the conventional way of using these terms in order to differentiate the "waste actinides" from uranium and plutonium.

In this thesis the term actinides is used, unless otherwise stated, to denote the heavy elements present in spent nuclear fuel in its original meaning, i.e., it includes the uranium and plutonium.

⁵. So is tritium, but with its relatively short half-life, it is not a long-term problem.

⁶. Within the United States military nuclear establishment alpha-bearing wastes are often called TRU waste, from "transuranic waste".

APPENDIX 2: LISTING OF CIVIL NUCLEAR REACTORS INCLUDED IN THE SCENARIO*

Country and IAEA Number	Reactor name	Net capacity (MW _e)	Construction start	Operational	Shut down	Planned operation	Reactor type
ARGENTINA							
AR-1	Atucha 1	335	1968	1974			PHWR
AR-2	Embalse	600	1974	1984			PHWR
AR-3	Atucha 2	692	1981			1994	PHWR
BELGIUM							
BE-1	BR-3	11	1957	1962	1987		PWR
BE-2	Doel 1	400	1969	1975			PWR
BE-3	Tihange 1	870	1970	1975			PWR
BE-4	Doel 2	400	1971	1975			PWR
BE-5	Doel 3	900	1975	1982			PWR
BE-6	Tihange 2	900	1976	1983			PWR
BE-7	Doel 4	1010	1978	1985			PWR
BE-8	Tihange 3	1020	1978	1985			PWR
BRAZIL							
BR-1	Angra 1	626	1971	1984			PWR
BR-2	Angra 2	1245	1976			1996	PWR
BULGARIA							
BG-1	Kozloduy 1	408	1970	1974			PWR
BG-2	Kozloduy 2	408	1970	1975			PWR
BG-3	Kozloduy 3	408	1973	1981			PWR
BG-4	Kozloduy 4	408	1973	1982			PWR
BG-5	Kozloduy 5	953	1980	1988			PWR
BG-6	Kozloduy 6	953	1984			1991	PWR
BG-7	Belene 1	953	1987			1992	PWR
CANADA							
CA-1	NPD	22	1958	1962	1987		PHWR
CA-2	Douglas Point	206	1960	1968	1984		PHWR
CA-4	Pickering 1	515	1966	1971			PHWR
CA-5	Pickering 2	515	1966	1971			PHWR
CA-6	Pickering 3	515	1967	1972			PHWR
CA-7	Pickering 4	515	1968	1973			PHWR
CA-8	Bruce 1	848	1971	1977			PHWR
CA-9	Bruce 2	848	1970	1977			PHWR
CA-10	Bruce 3	848	1972	1978			PHWR
CA-11	Bruce 4	848	1972	1979			PHWR
CA-12	Gentilly 2	640	1974	1983			PHWR
CA-13	Pickering 5	516	1974	1983			PHWR
CA-14	Pickering 6	516	1975	1984			PHWR
CA-15	Pickering 7	516	1976	1985			PHWR
CA-16	Pickering 8	516	1976	1986			PHWR
CA-17	Point Lepreau	635	1975	1983			PHWR
CA-18	Bruce 5	860	1978	1985			PHWR
CA-19	Bruce 6	860	1978	1984			PHWR
CA-20	Bruce 7	860	1979	1986			PHWR
CA-21	Bruce 8	860	1979	1987			PHWR
CA-22	Darlington 1	881	1982	1991			PHWR
CA-23	Darlington 2	881	1981	1990			PHWR
CA-24	Darlington 3	881	1984			1992	PHWR
CA-25	Darlington 4	881	1985			1993	PHWR

* The data is from IAEA (1991A), and represents the status of the reactors in the beginning of 1991. The only additions are the dates for planned operations for the former USSR reactors which have been estimated to be six years from start of construction. This actually means that some former USSR reactors are counted as already being completed, although they were not so in the beginning of 1991.

** PHWR=Pressurized Heavy Water Reactor, PWR=Pressurized Water Reactor, BWR=Boiling Water Reactor, GCR=Gas-cooled Reactor, AGR=Advanced Gas-cooled Reactor, LWGR=Light-water Graphite-Moderated Reactor.

Country and IAEA Number	Reactor name	Net capacity (MW _e)	Construction start	Operational	Shut down	Planned operation	Reactor type
CHINA							
CN-1	Qinshan	288	1985			1991	PWR
CN-2	Guangdong 1	930	1987			1992	PWR
CN-3	Guangdong 2	930	1988			1993	PWR
CZECHOSLOVAKIA							
CS-2	Bohunice 1	408	1974	1979			PWR
CS-3	Bohunice 2	408	1974	1981			PWR
CS-4	Dukovany 1	408	1978	1985			PWR
CS-5	Dukovany 2	408	1978	1986			PWR
CS-6	Mochovce 1	388	1983			1993	PWR
CS-7	Mochovce 2	388	1983			1995	PWR
CS-8	Dukovany 3	408	1978	1987			PWR
CS-9	Dukovany 4	408	1978	1987			PWR
CS-10	Mochovce 3	388	1985			1995	PWR
CS-11	Mochovce 4	388	1985			1995	PWR
CS-13	Bohunice 3	408	1976	1985			PWR
CS-14	Bohunice 4	408	1976	1986			PWR
CS-23	Temelin 1	892	1984			1992	PWR
CS-24	Temelin 2	892	1985			1994	PWR
FINLAND							
FI-1	Loviisa 1	445	1971	1977			PWR
FI-2	Loviisa 2	445	1972	1981			PWR
FI-3	Tvo 1	710	1974	1979			BWR
FI-4	Tvo 2	710	1975	1982			BWR
FRANCE							
FR-1	G-3 (Marcoule)	40	1956	1960	1984		GCR
FR-1B	G-2 (Marcoule)	39	1956	1959	1980		GCR
FR-2	Chinon A1	70	1957	1964	1973		GCR
FR-3	Chinon A2	180	1958	1965	1985		GCR
FR-4	Chinon A3	360	1961	1967	1990		GCR
FR-5	Chooz A (Ardennes)	305	1962	1967			PWR
FR-7	St Laurent A1	390	1963	1969	1990		GCR
FR-8	St Laurent A2	450	1966	1971			GCR
FR-9	Bugey 1	540	1968	1972			GCR
FR-11	Fessenheim 1	880	1971	1977			PWR
FR-12	Fessenheim 2	880	1972	1978			PWR
FR-13	Bugey 2	920	1972	1979			PWR
FR-14	Bugey 3	920	1973	1979			PWR
FR-15	Bugey 4	900	1974	1979			PWR
FR-16	Bugey 5	900	1975	1980			PWR
FR-17	St Laurent B1	915	1976	1983			PWR
FR-18	Tricastin 1	915	1974	1980			PWR
FR-19	Tricastin 2	915	1974	1980			PWR
FR-20	Gravelines 1	910	1975	1980			PWR
FR-21	Gravelines 2	910	1975	1980			PWR
FR-22	Dampierre 1	890	1975	1980			PWR
FR-23	St Laurent B2	880	1976	1983			PWR
FR-25	Tricastin 3	915	1975	1981			PWR
FR-26	Tricastin 4	915	1975	1981			PWR
FR-27	Gravelines 3	910	1975	1981			PWR
FR-28	Gravelines 4	910	1975	1981			PWR
FR-29	Dampierre 2	890	1975	1981			PWR
FR-30	Dampierre 3	890	1976	1981			PWR
FR-31	Dampierre 4	890	1976	1981			PWR
FR-32	Blayais 1	910	1977	1981			PWR
FR-33	Blayais 2	910	1977	1983			PWR
FR-34	Blayais 3	910	1978	1983			PWR
FR-35	Blayais 4	910	1978	1983			PWR
FR-36	Paluel 1	1330	1977	1985			PWR
FR-37	Paluel 2	1330	1978	1985			PWR
FR-38	Paluel 3	1330	1978	1986			PWR
FR-39	Paluel 4	1330	1979	1986			PWR
FR-40	Chinon B1	870	1977	1984			PWR
FR-41	Chinon B2	870	1977	1984			PWR
FR-42	Cruas 1	880	1978	1984			PWR
FR-43	Cruas 2	915	1978	1985			PWR

Country and IAEA Number	Reactor name	Net capacity (MW _e)	Construction start	Operational	Shut down	Planned operation	Reactor type
FRANCE (cont.)							
FR-44	Cruas 3	880	1979	1984			PWR
FR-45	Cruas 4	880	1979	1985			PWR
FR-46	Flammanville 1	1330	1980	1986			PWR
FR-47	Flammanville 2	1330	1982	1987			PWR
FR-48	St Alban 1	1335	1979	1986			PWR
FR-49	St Alban 2	1335	1979	1987			PWR
FR-50	Cattenom 1	1300	1979	1987			PWR
FR-51	Gravelines 5	910	1979	1985			PWR
FR-52	Gravelines 6	910	1979	1985			PWR
FR-53	Cattenom 2	1300	1980	1988			PWR
FR-54	Belleville 1	1310	1980	1988			PWR
FR-55	Belleville 2	1310	1980	1989			PWR
FR-56	Chinon B3	905	1980	1987			PWR
FR-57	Chinon B4	905	1981	1988			PWR
FR-58	Nogent 1	1310	1981	1988			PWR
FR-59	Nogent 2	1310	1981	1989			PWR
FR-60	Cattenom 3	1300	1982	1991			PWR
FR-61	Golfech 1	1310	1982	1991			PWR
FR-62	Chooz B1	1455	1984			1996	PWR
FR-63	Penly 1	1330	1982	1990			PWR
FR-64	Penly 2	1330	1984			1992	PWR
FR-65	Cattenom 4	1300	1983			1991	PWR
FR-68	Golfech 2	1310	1984			1993	PWR
FR-70	Chooz B2	1455	1985			1997	PWR
FR-72	Civaux 1	1455	1988			1997	PWR
GERMANY							
DE-1	Vak Kahl	15	1958	1962	1985		BWR
DE-2	MZFR	52	1961	1966	1984		PHWR
DE-3	Gundremmingen A (KRB)	237	1962	1967	1980		BWR
DE-5	Obriheim (KWO)	340	1965	1969			PWR
DE-6	Lingen (KWL)	240	1964	1968	1979		BWR
DE-7	HDR Grosswelzheim	23	1965	1970	1971		BWR
DE-9	Wuergassen (KWW)	640	1968	1975			BWR
DE-10	Stade (KKS)	640	1967	1972			PWR
DE-12	Biblis A	1146	1970	1975			PWR
DE-13	Brunsbuettel (KKB)	771	1970	1977			BWR
DE-14	Philippsburg 1 (KKP)	864	1970	1980			BWR
DE-15	Neckarwestheim 1 (GKN)	795	1971	1976			PWR
DE-16	Isar 1 (KKI)	870	1972	1979			BWR
DE-17	Unterweser (KKU)	1230	1972	1979			PWR
DE-18	Biblis B	1240	1972	1977			PWR
DE-20	Kruemmel	1260	1974	1984			BWR
DE-22	Mulheim-Kaerlich	1219	1975	1987			PWR
DE-23	Grafenrheinfeld (KKG)	1235	1975	1982			PWR
DE-24	Philippsburg 1 (KKP)	1268	1977	1985			PWR
DE-26	Gundremmingen B	1240	1976	1984			BWR
DE-27	Grohnde (KWG)	1300	1976	1985			PWR
DE-28	Gundremmingen C	1248	1976	1985			BWR
DE-31	Isar 2 (KKI)	1310	1982	1988			PWR
DE-32	Brokdorf (KBR)	1307	1981	1986			PWR
DE-33	Emsland (KKE)	1242	1982	1988			PWR
DE-44	Neckarwestheim 1 (GKN)	1225	1982	1989			PWR
DE-501	Rheinsberg (DD-1)	62	1960	1966	1990		PWR
DE-502	Greifswald 1 (DD-2)	408	1970	1974			PWR
DE-503	Greifswald 2 (DD-3)	408	1972	1975			PWR
DE-504	Greifswald 3 (DD-4)	408	1972	1978			PWR
DE-505	Greifswald 4 (DD-5)	408	1976	1979			PWR
DE-506	Greifswald 5 (DD-6)	408	1976	1989			PWR
HUNGARY							
HU-1	Paks 1	410	1974	1983			PWR
HU-2	Paks 2	415	1974	1984			PWR
HU-3	Paks 3	410	1979	1986			PWR
HU-4	Paks 4	410	1979	1987			PWR
INDIA							
IN-1	Tarapur 1	150	1964	1969			BWR
IN-2	Tarapur 2	150	1964	1969			BWR
IN-3	Rajasthan 1	207	1964	1973			PHWR

Country and IAEA Number	Reactor name	Net capacity (MW _e)	Construction start	Operational	Shut down	Planned operation	Reactor type
INDIA (cont.)							
IN-4	Rajasthan 2	207	1968	1981			PHWR
IN-5	Kalpakkam 1	220	1970	1984			PHWR
IN-6	Kalpakkam 2	220	1971	1986			PHWR
IN-7	Narora 1	220	1976	1991			PHWR
IN-8	Narora 2	220	1976			1991	PHWR
IN-9	Kakrapar 1	220	1983			1992	PHWR
IN-10	Kakrapar 2	220	1983			1993	PHWR
IN-11	Rajasthan 3	220	1988			1995	PHWR
IN-12	Rajasthan 4	220	1988			1996	PHWR
IN-13	Kaiga 1	220	1988			1995	PHWR
IN-14	Kaiga 2	220	1988			1996	PHWR
ITALY							
IT-1	Latina	153	1958	1964	1987		GCR
IT-2	Garigliano	150	1959	1964	1982		BWR
IT-3	Enrico Fermi (Trino)	260	1961	1965	1990		PWR
IT-4	Caorso	860	1970	1981	1990		BWR
JAPAN							
JP-1	JPDR II	9	1960	1965	1982		BWR
JP-2	Tokai 1	159	1960	1966			GCR
JP-3	Tsuruga 1	341	1966	1970			BWR
JP-4	Mihama 1	320	1967	1970			PWR
JP-5	Fukushima Daiichi 1	439	1967	1971			BWR
JP-6	Mihama 2	470	1968	1972			PWR
JP-7	Shimane 1	439	1970	1974			BWR
JP-8	Takahama 1	780	1970	1974			PWR
JP-9	Fukushima Daiichi 2	760	1969	1974			BWR
JP-10	Fukushima Daiichi 3	760	1970	1976			BWR
JP-11	Hamaoka 1	515	1971	1976			BWR
JP-12	Genkai 1	529	1971	1975			PWR
JP-13	Takahama 2	780	1971	1975			PWR
JP-14	Mihama 3	780	1972	1976			PWR
JP-15	Ohi 1	1120	1972	1979			PWR
JP-16	Fukushima Daiichi 4	760	1972	1978			BWR
JP-17	Fukushima Daiichi 5	760	1971	1978			BWR
JP-18	Fukushima Daiichi 6	1067	1973	1979			BWR
JP-19	Ohi 2	1120	1972	1979			PWR
JP-21	Tokai 2	1056	1973	1978			BWR
JP-22	Onagawa 1	496	1979	1984			BWR
JP-23	Ikata 1	538	1973	1977			PWR
JP-24	Hamaoka 2	806	1974	1978			BWR
JP-25	Fukushima Daini 1	1067	1975	1982			BWR
JP-26	Fukushima Daini 2	1067	1979	1984			BWR
JP-27	Genkai 2	529	1977	1981			PWR
JP-28	Sendai 1	846	1979	1984			PWR
JP-29	Takahama 3	830	1980	1985			PWR
JP-30	Takahama 4	830	1980	1985			PWR
JP-32	Ikata 1	538	1978	1982			PWR
JP-33	Kashiwazaki Kariwa 1	1067	1978	1985			BWR
JP-34	Tsuruga 2	1115	1982	1987			PWR
JP-35	Fukushima Daini 3	1067	1980	1985			BWR
JP-36	Hamaoka 3	1056	1982	1987			BWR
JP-37	Sendai 2	846	1981	1985			PWR
JP-38	Fukushima Daini 4	1067	1980	1987			BWR
JP-39	Kashiwazaki Kariwa 2	1067	1983	1990			BWR
JP-40	Kashiwazaki Kariwa 5	1067	1983	1990			BWR
JP-41	Shimane 1	790	1984	1989			BWR
JP-43	Tomari 1	550	1984	1989			PWR
JP-44	Tomari 2	550	1984	1991			PWR
JP-45	Genkai 3	1127	1988			1994	PWR
JP-47	Ikata 3	846	1986			1995	PWR
JP-48	Shika	513	1989			1993	BWR
JP-49	Hamaoka 4	1092	1989			1993	BWR
JP-50	Ohi 3	1127	1987			1991	PWR
JP-51	Ohi 4	1127	1987			1993	PWR
JP-52	Kashiwazaki Kariwa 3	1067	1987			1993	BWR
JP-53	Kashiwazaki Kariwa 4	1067	1988			1994	BWR
JP-54	Onagawa 2	796	1989			1995	BWR

Country and IAEA Number	Reactor name	Net capacity (MW _e)	Construction start	Operational	Shut down	Planned operation	Reactor type
KOREA (SOUTH)							
KR-1	Kori Unit 1 (KNU 1)	556	1971	1978			PWR
KR-2	Kori Unit 2 (KNU 2)	605	1977	1983			PWR
KR-3	Wolsong Unit 1 (KNU 3)	629	1977	1983			PHWR
KR-5	Kori Unit 3 (KNU 5)	895	1979	1985			PWR
KR-6	Kori Unit 4 (KNU 6)	895	1979	1986			PWR
KR-7	Yonggwang Unit 1 (KNU 7)	900	1980	1986			PWR
KR-8	Yonggwang Unit 2 (KNU 8)	900	1980	1987			PWR
KR-9	Ulchin Unit 1 (KNU 9)	920	1982	1988			PWR
KR-10	Ulchin Unit 2 (KNU 10)	920	1982	1989			PWR
KR-11	Yonggwang Unit 2 (KNU 8)	950	1989			1995	PWR
KR-12	Yonggwang Unit 2 (KNU 8)	950	1989			1996	PWR
NETHERLANDS							
NL-1	Dodeward	55	1965	1969			BWR
NL-2	Borssele	452	1969	1973			PWR
PAKISTAN							
PK-1	Kanupp	125	1966	1972			PHWR
ROMANIA							
RO-1	Cernavoda 1	625	1980			1993	PHWR
RO-2	Cernavoda 2	625	1982			1995	PHWR
RO-3	Cernavoda 3	625	1984			1997	PHWR
RO-4	Cernavoda 4	625	1984			1998	PHWR
RO-5	Cernavoda 5	625	1986			1999	PHWR
SOUTH AFRICA							
ZA-1	Koeberg 1	921	1976	1984			PWR
ZA-2	Koeberg 2	921	1976	1985			PWR
SPAIN							
ES-1	Jose Cabrera 1 (Zorita)	153	1964	1969			PWR
ES-2	Santa Maria de Garona	440	1966	1971			BWR
ES-3	Vandellós 1	480	1968	1972	1990		GCR
ES-6	Almaraz 1	900	1973	1981			PWR
ES-7	Almaraz 2	900	1973	1984			PWR
ES-8	Asco 1	898	1974	1983			PWR
ES-9	Asco 2	898	1975	1986			PWR
ES-10	Cofrentes	955	1975	1985			BWR
ES-11	Trillo 1	974	1979	1988			PWR
ES-16	Vandellós 2	949	1981	1988			PWR
SWEDEN							
SE-1	Ågesta	10	1957	1964	1974		PHWR
SE-2	Oskarshamn 1	442	1966	1972			BWR
SE-3	Oskarshamn 2	605	1969	1975			BWR
SE-4	Ringhals 1	750	1969	1976			BWR
SE-5	Ringhals 2	800	1970	1975			PWR
SE-6	Barsebäck 1	600	1971	1975			BWR
SE-7	Ringhals 3	915	1972	1981			PWR
SE-8	Barsebäck 2	600	1973	1977			BWR
SE-9	Forsmark 1	970	1973	1980			BWR
SE-10	Ringhals 4	915	1973	1983			PWR
SE-11	Forsmark 2	970	1975	1981			BWR
SE-12	Oskarshamn 3	1160	1980	1985			BWR
SE-14	Forsmark 3	1090	1979	1985			BWR
SWITZERLAND							
CH-1	Beznau 1	350	1965	1969			PWR
CH-2	Muehleberg	322	1967	1972			BWR
CH-3	Beznau 2	350	1968	1971			PWR
CH-4	Goesgen	920	1973	1979			PWR
CH-5	Leibstadt	990	1974	1984			BWR
TAIWAN							
TW-1	Chin Shan 1	604	1972	1978			BWR
TW-2	Chin Shan 2	604	1973	1979			BWR
TW-3	Kuosheng 1	948	1975	1981			BWR
TW-4	Kuosheng 2	948	1976	1983			BWR
TW-5	Maanshan 1	907	1978	1984			PWR
TW-6	Maanshan 2	907	1979	1985			PWR

Country and IAEA Number	Reactor name	Net capacity (MW _e)	Construction start	Operational	Shut down	Planned operation	Reactor type
UNITED KINGDOM							
GB-1A	Calder Hall Unit A	50	1953	1956			GCR
GB-1B	Calder Hall Unit B	50	1953	1957			GCR
GB-1C	Calder Hall Unit C	50	1955	1958			GCR
GB-1D	Calder Hall Unit D	50	1955	1959			GCR
GB-2A	Chapelcross Unit A	48	1955	1959			GCR
GB-2B	Chapelcross Unit B	48	1955	1959			GCR
GB-2C	Chapelcross Unit C	48	1955	1959			GCR
GB-2D	Chapelcross Unit D	48	1955	1959			GCR
GB-3A	Berkeley Unit A	138	1957	1962	1989		GCR
GB-3B	Berkeley Unit B	138	1957	1962	1988		GCR
GB-4A	Bradwell Unit A	123	1957	1962			GCR
GB-4B	Bradwell Unit B	123	1957	1962			GCR
GB-5	Windscale AGR	32	1958	1963	1981		AGR
GB-6A	Hunterston A1 Unit A	150	1957	1964	1990		GCR
GB-6B	Hunterston A2 Unit B	150	1957	1964	1989		GCR
GB-7A	Hinkley Point A Unit A	235	1957	1965			GCR
GB-7B	Hinkley Point A Unit B	235	1957	1965			GCR
GB-8A	Trawsfynydd Unit A	195	1959	1965			GCR
GB-8B	Trawsfynydd Unit B	195	1959	1965			GCR
GB-9A	Dungeness A Unit A	212	1960	1965			GCR
GB-9B	Dungeness A Unit B	212	1960	1965			GCR
GB-10A	Sizewell A Unit A	210	1961	1966			GCR
GB-10B	Sizewell A Unit B	210	1961	1966			GCR
GB-11A	Oldbury A Unit A	217	1962	1967			GCR
GB-11B	Oldbury A Unit B	217	1962	1968			GCR
GB-13A	Wylfa Unit B	438	1963	1971			GCR
GB-13B	Wylfa Unit B	438	1963	1972			GCR
GB-16A	Hinkley Point B Unit A	560	1967	1978			AGR
GB-16B	Hinkley Point B Unit B	560	1967	1976			AGR
GB-17A	Hunterston B1	575	1967	1976			AGR
GB-17B	Hunterston B2	575	1967	1977			AGR
GB-18A	Dungeness B1	415	1965	1985			AGR
GB-18B	Dungeness B2	415	1965	1989			AGR
GB-19A	Hartlepool A1	510	1968	1989			AGR
GB-19B	Hartlepool A2	510	1968	1989			AGR
GB-20A	Heysham 1 Unit A	510	1970	1989			AGR
GB-20B	Heysham 1 Unit B	510	1970	1989			AGR
GB-22A	Heysham 2 Unit A	615	1980	1989			AGR
GB-22B	Heysham 2 Unit B	615	1980	1989			AGR
GB-23	Torness Unit A	625	1980	1988			AGR
GB-23	Torness Unit B	625	1980	1989			AGR
GB-24	Sizewell B	1188	1988			1994	PWR
USA							
US-1	Elk River	22	1959	1964	1968		BWR
US-3	Indian Point 1	257	1956	1962	1974		PW
US-4	Bonus	17	1960	1964	1968		BWR
US-10	Dresden 1	192	1956	1960	1978		BWR
US-29	Yankee NPS	169	1957	1961			PWR
US-130	Pathfinder	59	1959	1966	1967		BWR
US-133	Humboldt Bay	63	1960	1963	1976		BWR
US-144	CVTR	17	1960	1963	1967		PHWR
US-155	Big Rock Point	69	1960	1963			BWR
US-206	San Onofre 1	436	1964	1968			PWR
US-213	Haddam Neck	569	1964	1968			PWR
US-219	Oyster Creek	620	1964	1969			BWR
US-220	Nine Mile Point 1	610	1965	1969			BWR
US-237	Dresden 2	772	1966	1970			BWR
US-244	RE Ginna	470	1966	1970			PWR
US-245	Millstone 1	654	1966	1971			BWR
US-247	Indian Point 2	864	1966	1974			PWR
US-249	Dresden 3	773	1966	1971			BWR
US-250	Turkey Point 3	666	1967	1972			PWR
US-251	Turkey Point 4	666	1967	1973			PWR
US-254	Quad Cities 1	769	1967	1973			BWR
US-255	Palisades	730	1967	1971			PWR

Country and IAEA Number	Reactor name	Net capacity (MW _e)	Const- ruction start	Opera- tional	Shut down	Planned operation	Reactor type
USA (cont.)							
US-259	Browns Ferry 1	1065	1967	1974			BWR
US-260	Browns Ferry 2	1065	1967	1975			BWR
US-261	HB Robinson 2	665	1967	1971			PWR
US-263	Monticello	536	1967	1971			BWR
US-265	Quad Cities 2	769	1967	1973			BWR
US-266	Point Beach 1	485	1967	1970			PWR
US-269	Oconee 1	860	1967	1973			PWR
US-270	Oconee 2	860	1967	1974			PWR
US-271	Vermont Yankee	504	1967	1972			BWR
US-272	Salem 1	1079	1968	1977			PWR
US-275	Diablo Canyon 1	1084	1968	1985			PWR
US-277	Peach Bottom 2	1051	1968	1974			BWR
US-278	Peach Bottom 3	1035	1968	1974			BWR
US-280	Surry 1	781	1968	1972			PWR
US-281	Surry 2	775	1968	1973			PWR
US-282	Prairie Island	503	1968	1973			PWR
US-285	Fort Calhoun 1	438	1968	1974			PWR
US-286	Indian Point 2	965	1968	1976			PWR
US-287	Oconee 3	860	1967	1974			PWR
US-289	Three Mile Island 1	776	1968	1974			PWR
US-293	Pilgrim 1	670	1968	1972			BWR
US-295	Zion 1	1040	1968	1973			PWR
US-296	Browns Ferry 3	1065	1968	1977			BWR
US-298	Cooper	764	1968	1974			BWR
US-301	Point Beach 2	485	1968	1972			PWR
US-302	Crystal River 3	821	1967	1977			PWR
US-304	Zion 2	1040	1968	1974			PWR
US-305	Kewaunee	503	1968	1974			PWR
US-306	Prairie Island	500	1969	1974			PWR
US-309	Maine Yankee	810	1968	1972			PWR
US-311	Salem 2	1106	1968	1981			PWR
US-312	Rancho Seco 1	873	1969	1975			PWR
US-313	Arkansas One 1	836	1968	1974			PWR
US-315	Donald Cook 1	1020	1969	1975			PWR
US-316	Donald Cook 2	1060	1969	1978			PWR
US-317	Calvert Cliffs 1	825	1968	1975			PWR
US-318	Calvert Cliffs 2	825	1968	1975			PWR
US-320	Three Mile Island 2	905	1969	1978	1979		PWR
US-321	Hatch 1	752	1968	1975			BWR
US-323	Diablo Canyon 2	1093	1970	1986			PWR
US-324	Brunswick 2	790	1969	1975			BWR
US-325	Brunswick 1	790	1969	1977			BWR
US-327	Sequoyah 1	1148	1970	1981			PWR
US-328	Sequoyah 2	1148	1970	1982			PWR
US-331	Duane Arnold 1	515	1970	1975			BWR
US-333	Fitzpatrick	810	1968	1975			BWR
US-334	Beaver Valley 1	810	1970	1976			PWR
US-335	St Lucie 1	827	1970	1976			PWR
US-336	Millstone 2	857	1969	1975			PWR
US-338	North Anna 1	893	1971	1978			PWR
US-339	North Anna 2	893	1970	1980			PWR
US-341	Enrico Fermi 2	1154	1969	1987			BWR
US-344	Trojan	1080	1970	1976			PWR
US-346	Davis Besse 1	860	1970	1978			PWR
US-348	Farley 1	816	1970	1977			PWR
US-352	Limerick 1	1065	1970	1986			BWR
US-353	Limerick 2	1055	1970	1990			BWR
US-354	Hope Creek 1	1067	1976	1986			BWR
US-361	San Onofre 2	1070	1974	1983			PWR
US-362	San Onofre 3	1070	1974	1984			PWR
US-364	Farley 2	807	1970	1981			PWR
US-366	Hatch 1	748	1972	1979			BWR
US-368	Arkansas One 2	858	1971	1980			PWR
US-369	McGuire 1	1180	1971	1981			PWR
US-370	McGuire 2	1180	1971	1984			PWR
US-373	Lasalle 1	1036	1973	1984			BWR
US-374	Lasalle 2	1078	1973	1984			BWR

Country and IAEA Number	Reactor name	Net capacity (MW _e)	Construction start	Operational	Shut down	Planned operation	Reactor type
USA (cont.)							
US-382	Waterford 3	1104	1974	1985			PWR
US-387	Susquehanna 1	1032	1973	1983			BWR
US-388	Susquehanna 2	1032	1973	1985			BWR
US-389	St Lucie 2	837	1976	1983			PWR
US-390	Watts Bar 1	1165	1972			1992	PWR
US-395	Virgil C Summer 1	885	1973	1984			PWR
US-397	WPPSS 2	1095	1972	1984			BWR
US-400	Shearon Harris 1	900	1974	1987			PWR
US-409	Lacrosse	48	1963	1969	1987		BWR
US-410	Nine Mile Point 2	1080	1975	1988			BWR
US-412	Beaver Valley 1	833	1974	1987			PWR
US-413	Catawba 1	1145	1974	1985			PWR
US-414	Catawba 2	1145	1974	1986			PWR
US-416	Grand Gulf 1	1108	1974	1985			BWR
US-423	Millstone 3	1159	1974	1986			PWR
US-424	Vogtle 1	1122	1976	1987			PWR
US-425	Vogtle 2	1083	1976	1989			PWR
US-440	Perry 1	1205	1974	1987			BWR
US-443	Seabrook 1	1149	1976	1990			PWR
US-445	Comanche Peak 1	1150	1974	1990			PWR
US-454	Byron 1	1129	1975	1985			PWR
US-455	Byron 2	1129	1975	1987			PWR
US-456	Braidwood 1	1120	1975	1988			PWR
US-457	Braidwood 2	1120	1975	1988			PWR
US-458	River Bend 1	934	1977	1986			BWR
US-461	Clinton 1	951	1975	1987			BWR
US-482	Wolf Creek	1128	1977	1985			PWR
US-483	Callaway 1	1120	1975	1984			PWR
US-498	South Texas 1	1250	1975	1988			PWR
US-499	South Texas 2	1250	1975	1989			PWR
US-528	Palo Verde 1	1221	1976	1986			PWR
US-529	Palo Verde 2	1304	1976	1986			PWR
US-530	Palo Verde 3	1304	1976	1988			PWR
USSR (FORMER)							
SU-3	Beloyarsky 1	102	1958	1964	1983		LWGR
SU-4	Novovoronezh 1	197	1957	1964	1988		PWR
SU-6	Beloyarsky 2	146	1956	1969	1990		LWGR
SU-8	Novovoronezh 2	336	1964	1970	1990		PWR
SU-9	Novovoronezh 3	385	1967	1972			PWR
SU-11	Novovoronezh 4	385	1967	1973			PWR
SU-12	Kola 1	411	1970	1973			PWR
SU-13	Kola 2	411	1973	1975			PWR
SU-14A	Bilibino Unit A	11	1970	1974			LWGR
SU-14B	Bilibino Unit B	11	1970	1975			LWGR
SU-14C	Bilibino Unit C	11	1970	1976			LWGR
SU-14D	Bilibino Unit D	11	1970	1976			LWGR
SU-15	Leningrad 1	925	1970	1974			LWGR
SU-16	Leningrad 2	925	1970	1976			LWGR
SU-17	Kursk 1	925	1972	1977			LWGR
SU-18	Armenia 1	376	1973	1977	1989		PWR
SU-19	Armenia 2	376	1975	1977	1989		PWR
SU-20	Novovoronezh 5	950	1974	1981			PWR
SU-22	Kursk 2	925	1973	1979			LWGR
SU-23	Smolensk 1	925	1975	1983			LWGR
SU-24	Smolensk 2	925	1976	1985			LWGR
SU-25	Chernobyl 1	950	1972	1978			LWGR
SU-26	Chernobyl 2	950	1972	1979			LWGR
SU-27	Rovno 1	361	1976	1981			PWR
SU-28	Rovno 2	384	1977	1982			PWR
SU-29	Rovno 3	950	1981	1987			PWR
SU-30	Kalinin 1	953	1977	1984			PWR
SU-31	Kalinin 2	953	1982	1987			PWR
SU-32	Kola 3	411	1976	1982			PWR
SU-33	Kola 4	411	1977	1985			PWR
SU-34	Leningrad 3	925	1973	1980			LWGR
SU-35	Leningrad 4	925	1975	1981			LWGR
SU-36	Kalinin 3	950	1985			1991	PWR

Country and IAEA Number	Reactor name	Net capacity (MW _e)	Construction start	Operational	Shut down	Planned operation	Reactor type
USSR (FORMER) (cont.)							
SU-37	Kalinin 4	950	1986			1992	PWR
SU-38	Kursk 3	925	1978	1983			LWGR
SU-39	Kursk 4	925	1981	1986			LWGR
SU-40	Khmelnitski 1	950	1981	1985			PWR
SU-41	Khmelnitski 2	950	1986			1992	PWR
SU-42	Chernobyl 3	950	1977	1982			LWGR
SU-43	Chernobyl 4	950	1979	1984	1986		LWGR
SU-44	South Ukraine 1	950	1977	1983			PWR
SU-45	South Ukraine 2	950	1979	1985			PWR
SU-46	Ignalina 1	1450	1977	1985			LWGR
SU-47	Ignalina 2	1450	1978	1987			LWGR
SU-48	South Ukraine 3	950	1985	1989			PWR
SU-49	South Ukraine 4	950	1987			1993	PWR
SU-51	Khmelnitski 3	950	1986			1992	PWR
SU-52	Khmelnitski 4	950	1987			1993	PWR
SU-54	Zaporozhe 1	950	1980	1985			PWR
SU-56	Zaporozhe 2	950	1981	1986			PWR
SU-59	Rostov 1	950	1981			1987	PWR
SU-60	Bashkir 1	950	1983			1989	PWR
SU-62	Rostov 2	950	1983			1989	PWR
SU-63	Rostov 3	950	1989			1995	PWR
SU-67	Smolensk 3	925	1984	1990			LWGR
SU-68	Smolensk 4	925	1984			1990	LWGR
SU-69	Rovno 4	950	1986			1992	PWR
SU-72	Ingalina 3	1380	1985			1991	LWGR
SU-78	Zaporozhe 3	950	1982	1987			PWR
SU-79	Zaporozhe 4	950	1984	1988			PWR
SU-85	Bashkir 2	950	1983			1989	PWR
SU-92	Tatar 1 (KAMA)	950	1987			1993	PWR
SU-93	Tatar 2 (KAMA)	950	1988			1994	PWR
SU-96	Balakovo 1	950	1980	1986			PWR
SU-97	Balakovo 2	950	1981	1988			PWR
SU-98	Balakovo 3	950	1982	1989			PWR
SU-99	Balakovo 4	950	1984			1990	PWR
SU-114	Balakovo 5	950	1987			1993	PWR
SU-115	Balakovo 6	950	1988			1994	PWR
SU-120	Kursk 5	925	1985			1991	LWGR
SU-121	Kursk 6	925	1986			1992	LWGR
SU-126	Zaporozhe 5	950	1985	1989			PWR
SU-127	Zaporozhe 6	950	1986			1992	PWR
SU-130	Gorkiy (heat only)	500	1982			1988	PWR
SU-131	Voronezh (heat only) 1	500	1983			1989	PWR
SU-135	Voronezh (heat only) 2	500	1985			1991	PWR
YUGOSLAVIA							
YU-1	Krsko	632	1975	1983			PWR

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* An untranslatable pun on the name Kynnefjäll.

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* This report was translated into Swedish as *Los Alamosrapporten: Politiska frågor kring den framtida produktionen av speciellt klyvbart material*, Solserien nr 1/1983, Folkkampanjen mot kärnkraft [The People's Campaign Against Nuclear Power]. It was claimed that it was a secret US report, and this may have been the case at that time. Now, however the report is marked "Distribution of this report is unlimited" and there are no signs of a previous classification.

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