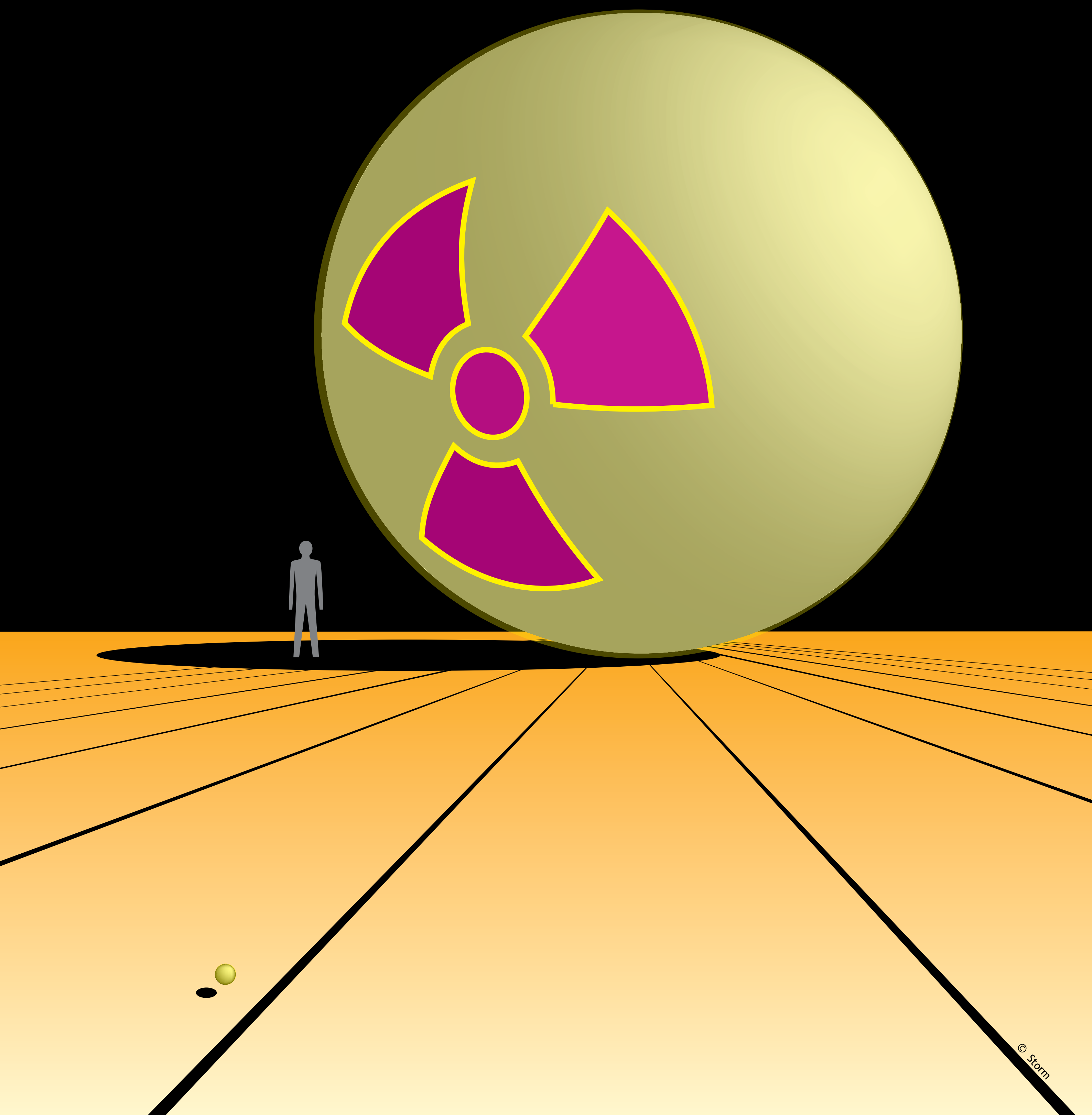
Nuclear Security

in cauda venenum



Nuclear Security

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Ceedata Consultancy

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In cauda venenum
A Latin phrase from ancient Rome, meaning: the poison is in the tail. Using the metaphor of a scorpion, this can be said of a story or a development that seems to proceed gently, but turns vicious towards the end.

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With this study WISE hopes to contribute to a thorough debate on the issue of nuclear security. It is not an easy debate and it is of utmost importance to exchange ideas, views and well-researched arguments and facts. We alle share the desire for a safe world free of nuclear disasters. We will only get there if we dare to face the challenges, even if they are more complicated than often said.

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Peer de Rijk, director WISE International

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Summary

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A unique feature of applied nuclear technology is the generation of fissile materials and massive amounts of human-made radioactivity. As a result civil nuclear technology raises unique hazards and security issues, encompassing a number of pathways along which severe damage can be inflicted to the political, economic and societal stability on a regional, national or even global scale:

- Terroristic use of nuclear explosives.
- Proliferation of critical nuclear technology to politically unstable countries.
- Armed conflicts involving nuclear installations and materials.
- Terroristic attacks with conventional weapons on nuclear installations containing fissile materials and large amounts of highly radioactive materials: nuclear power plants, spent fuel cooling pools and reprocessing plants.
- Severe accidents involving one of above mentioned installations.

The consequences of the last two potential events are indistinguishable: both cause large-scale dispersion of massive amounts of human-made radioactivity over vast regions, affecting millions of people.

Scope

Military issues are not addressed here, although military and civil nuclear technology are inextricably intertwined. This study discusses three aspects of nuclear security. For that reason this report is divided into three parts:

- The first part covers the origin of artificial fissile materials and human-made radioactivity from civil nuclear power reactors, and how these materials could play a role in terroristic actions and the equivalent impacts of accidental onsite events.
- The second part covers the role of computer models in the perception of nuclear security. and the role of natural phenomena which make inherently safe nuclear systems impossible. Further it addresses the mechanisms of Chernobyl-class disasters and their increasing likelihood.
- The third part discusses the strained relationship between at one hand the economic paradigm and the downplay culture of the nuclear industry plus the entanglement of interests, and nuclear security on the other hand,

Terroristic nuclear explosives

In principle there are five different fissile materials which can be used foor atomic bombs: highly enriched uranium (HEU), uranium-233, plutonium, neptunium and americium. Except HEU these materials become available in separated form by reprocessing of spent nuclear fuel. By theft terrorists could acquire sufficient materials to fabricate a crude nuclear bomb. Without reprocessing the only way to obtain bomb material is enrichment of uranium to a high U-235 assay (HEU).

Safeguards of the fissile materials in a reprocessing plant cannot be perfect: 1-5% of the materials are unaccounted for due to unavoidable, and often unnoticed, process losses. The risks of plutonium theft are high due to the frequent transports of separated plutonium and the MOX fuel that is made from uranium and plutonium for use in conventional power reactors. MOX fuel (Mixed OXide) can be used to make a crude nuclear weapon, without advanced technology.

There are reasons of concern regarding the security of the stockpiles uf uranium-233.

Neptunium and americium are not safeguarded internationally.

Illicit trafficking and theft

Another cause for concern is illegal trade and smuggling of nuclear materials, only a small step from nuclear criminality and terrorism. Transports of hazardous materials are difficult to detect, when detection is even possible. This problem increases with time due to increasing amounts of radioactive materials and declining inspections. One of the consequences is the uncontrolled release of radioactive materials into the public domain and insidious exposure of a growing number of people to radionuclides. Serious accidents and terroristic actions cannot be ruled out. Political instability, for whatever reason, exaggerates the risks of illicit nuclear transports with malicious intent.

Chernobyl-class disasters

Serious disruption of political, economical and societal stability could also result from a large-scale release of radioactive materials caused by a terroristic attack with conventional explosives on a nuclear power plant, spent fuel cooling pool, or reprocessing plant. The consequences of such an attack could develop into a Chernobyl-class disaster.

Spent nuclear fuel has to be actively cooled for many years after discharge from the reactor due to its residual heat generation. Interruption of the cooling before the required period of time, and depending on the age of the spent fuel, will inevitably lead to meltdown of the fuel elements. A number of mechanisms are conceivable - some of which have actually occured - which could cause a fuel meltdown. At high temperatures the cladding of the nuclear fuel reacts with water, generating hydrogen. Violent steam and hydrogen explosions coupled with the dispersion of tremendous amounts of human-made radioactivity into the environment are unavoidable. The contaminated areas could cover 100 000-200 000 square kilometers and millions of people might be affected, as happened in the Chernobyl and Fukushima disasters.

Installations vulnerable to the above scenario are nuclear reactors and on-site and off-site spent fuel cooling pools. Each year an operating nuclear reactor generates about 1000 nuclear bomb equivalents of human-made radioactivity, a spent fuel cooling pond contains an even greater amount. A reprocessing plant may contain 0.1 to 1 million nuclear bomb equivalents, distributed over thousands of tonnes of conditioned and unconditioned, liquid and solid wastes, and spent fuel in cooling pools awaiting reprocessing. Violent explosions and meltdown of fuel are also possible in reprocessing plants. Possible triggers of such a scenario are accidents, natural disasters, human failures and terroristic actions.

Reprocessing of spent fuel

Assessing the whole chain of processes and activities related to nuclear power and the security issues they raise, one component of the chain stands out: the reprocessing of spent fuel. By reprocessing bomb-usable fissile materials, plutonium, neptunium and americium, are separated from spent fuel and become in principle available to terrorists for making nuclear explosives. In the sequence of reprocessing the highly radioactive fission products are dispersed over large volumes of solid, liquid and gaseous wastes, and the radioactive gases are released into the environment. The bulk of the remaining radioactive waste is stored in the reprocessing plants in an easily dispersible form. Due to cumulation over decades these amounts of dangerous highly radioactive reprocessing wastes are immense and the risks of dispersion into the environment are growing over time.

In spent fuel the fissile materials and fission products are in the most condensed condition and in the least accessible form for malicious actions. Each operation which breaks the integrity of the fuel elements enhances the security risks and renders safe definitive disposal of the extremely radioactive material much more expensive.

The environmental and security problems raised by reprocessing of spent fuel would increase even more if closed-cycle reactors (breeders) and partitioning & transmutation (P&T) systems were to come on line. With these systems massive amounts of plutonium and other fissile materials would be separated, shipped and spread amongst numerous vulnerable facilities. In addition the amounts of high-level radioactive waste, mainly in easily dispersible form, would greatly increase due to the repeated reprocessing of the spent fuel in these closed-cycle systems.
Fortunately breeders and P&T systems have proved to be technically unfeasible, due to facts the designers of these advanced systems did not account for. Conditio sine qua non of the breeder and P&T systems is the availability of perfect materials and the possibility of complete separation of a complex mixture of highly radioactive chemical species into pure fractions. Both conditions are impossible, as follows from the Second Law of thermodynamics.

Reprocessing turns out to be an exceedingly polluting and expensive technology which became essentially superfluous when the breeder and P&T systems proved to be unfeasible. The use of MOX fuel in conventional light-water reactors has a negative energy balance and raises serious security problems. Other purposes of reprocessing as proposed by the nuclear industry are based on fallacies, or are impractical for various reasons.

Reliance on computer models

Computer models are widely used in the nuclear world, not only to assess nuclear security issues, but also to estimate radiation doses for individuals and populations of areas contaminated by radioactive materials and to estimate the expected health effects of exposure to radioactivity.
Each computer model has its inherent limitations by definition, in addition to the limitations set by the choices of the variables incorporated into the model and the choices of the values of the model parameters. Generally the models are applied rigidly, incorporating little or no practical evidence even as this evidence becomes available as time goes by.

Inherent safe nuclear power is inherently impossible

Computer models, regulations and safeguards usually start from as-designed quality of nuclear installations and perfect supervision of quality and operations. According to the reactor safety model studies of the nuclear industry a large-scale accident could be expected once every 2500 years. Empirical evidence proves this frequency to be once every 10-20 years, so the models have little practical application.
Nuclear installations are subject to the bathtub hazard function, like any technical construction and living organism. The bathtub hazard function implies that the failure rate rises exponentially during the wear-out phase. This phase follows an operational life during a number of years at a relatively low rate of failures. The rising failure rate is caused by unavoidable ageing processes governed by the Second Law of thermodynamics. In addition human behavior is an unquantifiable and unpreventable risk factor. Therefore inherent safe nuclear reactors are inherently impossible, let alone inherently safe nuclear power. This includes the whole system of industrial activities needed to generate nuclear power (the nuclear fuel chain or fuel cycle).

Despite empirical evidence of the shortcomings the nuclear industry shows an unshakeable faith in its technical models and paper regulations, often ignoring the fact that not all relevant processes and phenomena are known and that not all factors are predictable and quantifiable. In proposed advanced technical concepts the nuclear industry does not show any notion of the implications of the Second Law of thermodynamics with respect to the feasibility of those concepts.

Radiation protection models

The official radiation protection models for assessment of health hazards posed by radioactive materials are based on a limited set of variables and parameters. Biological behavior of any one kind of radionuclide inside the human body is not accounted for in the models, let alone the biological behavior of a number of different kinds of radionuclides acting simultaneously. Chronic exposure to radionuclides, for example via food and drinking water in a contaminated area, is not included either.

Due to the long latency periods and anonymous character of stochastic health effects, it is rarely possible to attribute a certain disease of an individual to radioactive contamination. The relationship between exposure to radioactive contamination and its detrimental health effects can only be demonstrated in a statistical way by means of epidemiological studies involving very large numbers of people during many years.
The nuclear world recognizes only deterministic health effects as radiation-induced; these effects occur after exposure to very high radiation doses. Official nuclear institutes do not recognize non-cancer diseases as possibly radiation-induced and systematically attribute them to non-nuclear causes, without backing by scientific investigation.
Empirical evidence from previous events is not incorporated in the official assessments of health hazards of nuclear accidents. The applied exposure and effect models have a strong economic component and can easily be adapted to the political and economic needs of a given moment and/or place.
Economic principles play a dominant role in the recommendations of the International Commission on Radiological Protection (ICRP) for allowed exposure of the general public and individuals to nuclear radiation. These recommendations generally form the basis of the policy of governments on the subject of radioactivity.

The faith of the International Atomic Energy Agency and other official nuclear institutes in computer models can be so rigid that empirical observations that are not compatible with the radiation protection models are systematically dismissed as irrelevant, without any scientific evidence. This is found in, among other, the official reports on the health effects in the affected regions after the Chernobyl disaster.

Economic preferences and nuclear security

Economic preferences and commercial choices can greatly increase nuclear security risks. The numerous violations of the Non-Proliferation Treaty probably have economic background. Hardly other than short-term economic motives can be conceived for reprocessing of spent fuel and the use of MOX fuel in conventional reactors.
Then there is the relaxation of the official standards for operational routine discharges of radionuclides into the environment by nuclear power plants and reprocessing plants. Due to ageing the frequency of leaks and spills will rise at an accelerated rate and so will the costs to repair the leaks and to prevent their occurrence. Raising allowable radioactive discharge limits for the nuclear operators keeps their costs down, while resulting in higher exposure standards for the general public, often by large factors, without scientific justification. Similar relaxation of exposure standards may be expected in case of a future nuclear accident, as occurred after the Fukushima disaster.
Another example is the relaxation of standards for clearance of radioactive construction materials for unrestricted use in the public domain. This will become a hot issue when heavily contaminated nuclear installations are dismantled; safe guardianship and disposal of the massive amounts of radioactive debris and scrap will be very expensive.
Economic reasons push the trend of lifetime extension for of nuclear power stations beyond the designed lifetime of 40 years. It is not clear how the owners of the plants and the supervisory institutes incorporate

the unavoidable ageing and the bathtub function in their security assessments, or how independent or how thorough the inspections are.

Entanglement of interests

Information to the general public on nuclear matters is dominated by the authoritive International Atomic Energy Agency (IAEA), often called the 'nuclear watchdog'. The IAEA has the promotion of nuclear power in its mission statement and its official publications have to be approved by all its member states. For these reasons it is a misconception to view the IAEA as an independent scientific institute. Besides dominating the public relations of the nuclear industry, the IAEA dominates also the publications of the International Commission on Radiological Protection (ICRP) and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The views of the World Nuclear Association (WNA) and Nuclear Energy Agency (OECD-NEA) rely heavily on the IAEA. The World Health Organization (WHO) cannot operate and publish independently of the IAEA on nuclear matters. For that reason statements of the WHO on nuclear matters do not deviate from the IAEA statements.
The long latency periods and the non-specific character give the nuclear industry ample opportunity to play down the health effects of radioactive contamination.

Après nous le déluge: heading for a future disaster

The chances of nuclear terrorism and of Chernobyl-class nuclear accidents are greatly increasing as long as the nuclear industry upholds in its current frame of mind, characterized by a short time horizon, living on credit and an *après nous le déluge* attitude. Nuclear security problems and associated health hazards are growing with time and will persist for the next century, even were the world's nuclear power stations to all be closed down today.

Effective and durable isolation from the biosphere of all radioactive wastes, including spent fuel, fissile materials and the future decommissioning and dismantling wastes, is the only way out of the mounting hazards of the nuclear heritage. The involved activities will require unprecedented investments of energy, materials, human resources and economic means, to be measured in trillions of euros. These future investments will not contribute to the improvement of the economic infrastructure and must be considered to be pure losses. Even if the last nuclear power plant could be shut down today, the economy would have to sustain a nuclear workforce to perform the demanding task of decommissioning and dismantling far beyond the year 2100. This workforce does not contribute to any improvement of the energy supply. Its sole task is to prevent the many disastrous consequences of the nuclear legacy. One might wonder if enough young people would opt for the required rigorous education and training, and if a free market-oriented economy would be able to support such a workforce for such a long period with no return on investments. What are the prospects of that in times of a declining economy?
Serious nuclear security problems and large-scale disasters seem inevitable.

Introduction

A unique feature of applied nuclear technology is the generation of fissile materials from non-fissile materials and the generation of tremendous amounts of human-made radioactivity. Radioactivity is harmful and dangerous to humans and cannot be destroyed nor made harmless.

Nuclear technology has two faces: a military one and a civil one. Consequently nuclear security concerns military as well as civil aspects. Military and civil nuclear technology are inseparable. Specificly military applications of nuclear technology (e.g. weapons and nuclear propulsion) are not discussed here. This report focuses on the security and safety issues raised by civil applications of nuclear technology.

Nuclear security is a complex issue, involving all aspects of nuclear technology which could inflict serious damage to (geo)political, economic and societal stability. Of primary concern are the possibilities of terroristic attacks with nuclear explosives. Little less worrisome however might be the possibilities of Chernobyl-scale dispersion of massive amounts of radioactivity in the public domain, either by terroristic attacks with conventional explosives, or by accident: the consequences are indistinguishable.

Two kinds of nuclear materials are important in this respect:

- fissile materials suitable to fabricate nuclear explosives: highly enriched uranium (HEU), uranium-233, plutonium, neptunium and americium,
- highly radioactive materials: spent fuel, reprocessing wastes and other materials.

How are the potential pathways for terroristic groups to acquire and use nuclear explosives?
How are the possible pathways of events leading to Chernobyl-scale dispersion of human-made radioactivity into the human environment?

This report addresses three inextricable aspects of nuclear security, for that reason it is divided into three parts:

Part A — Nuclear security and malicious actions
Origin and availability of fissile materials and of highly radioactive materials.
Potential terroristic actions with nuclear explosives.

Part B — Security and civil nuclear power
Models, physical laws and empirical evidence. Mechanisms of Chernobyl-scale disasters.
Non-nuclear terroristic attacks causing severe damage.

Part C — Nuclear security and economics
Energy on credit. Flexible standards. Entanglement of interests. Putting responsibilities off.
Heading for future disasters: in cauda venenum.

PART **A** NUCLEAR SECURITY AND MALICIOUS ACTIONS

1 Nuclear explosives

Uranium

An atomic bomb can be made from materials containing sufficient fissile nuclides to sustain a divergent fission chain reaction. Uranium as found in nature contains 0.7% uranium-235, the only fissile nuclide occurring in nature. The remaining 99.3% consists of U-238 and traces of U-234, both nuclides are not fissile. Natural uranium is not suitable for bombs, it has to be enriched in U-235 to make a nuclear explosion possible. In this context often the designations HEU (highly enriched uranium) and LEU (low enriched uranium) are used. LEU contains less than 20% U-235 and is considered to be not weapon-usable, HEU usually contains 90% U-235 or more (weapons grade), but uranium at any enrichment assay higher than 20% is often also called HEU. The global stockpile of HEU, equivalent with 90% enriched HEU, was 1390 kg as of January 2013 (IPFM 2013).

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Each kind of fissile materials has a specific critical mass, that is the minimum mass required to sustain a explosiove fission chain reaction. The diameter and mass of a critical sphere of uranium decline with rising enrichment assay and with the thickness of the neutron reflector (beryllium, graphite). The bare-sphere critical mass of enriched uranium declines from 1351 kg at 15% U-235 to 53.3 kg at 93% U-235 (weapons-grade uranium). The corresponding diameters are 51.4 cm respectively 17.5 cm. With a neutron reflector of 15 cm thickness the figures are much lower: 253.8 kg and 20.4 cm, respectively 11.7 kg and 10.6 cm (Glaser 2005).

Technology needed to make nuclear bombs from fissile material is available outside of the established nuclear-armed countries and in the open literature, as the Nth Country Experiment proved (Frank 1967, Schneider 2007).

Enrichment of uranium

Enrichment is a technique for separating natural uranium into two fractions: a large fraction containing less than 0.7% U-235 (called depleted uranium) and a smaller fraction containing more than 0.7% (U-235 enriched uranium). Obviously the depleted uranium fraction will be larger as the U-235 content of the enriched uranium is higher. To produce 1 kg weapons-grade uranium (93% U-235) 22.5 kg natural uranium has to be processed, leaving a waste of 21.5 kg depleted uranium (DU) at an assay of 0.3% U-235.

It is possible to apply civil nuclear technology for the production of nuclear weapons. By means of commercial enrichment technology bomb-grade uranium can be produced. The currently applied techniques are diffusion and ultracentrifuge. Both techniques require large plants and a substantial energy input, especially the diffusion technique.

A new uranium enrichment technique approved by the US Nuclear Regulatory Commission could have an impact on nuclear proliferation (*Nature*, 4 October 2012, p.5). The new technique is based on lasers and will require considerably less space and electricity than the existing techniques (diffusion and ultracentrifuge). Laser enrichment facilities are much easier to hide for international inspections. GE-Hitachi, the multinational company pursuing laser enrichment, describes it as a “game-changing technology”. The possibility exists that laser enrichment facilities might be undetectable. Mistrust could lead to regional arms race and even to open conflicts.

Uranium-233

Uranium-233 is a fissile nuclide that is prepared from non-fissile thorium -232 by neutron irradiation in a nuclear reactor. After irradiation the thorium target elements are to be reprocessed to separate the U-233 from the remaining Th-232. U-233 has been used during the 1950s and 1960s in the development of nuclear rockets, nuclear ramjets for an atomic bomber, but also for civil power reactors. These technical developments were halted in the 1970s, apparently due to various problems. One of these problems is the presence of uranium-232, a strong gamma-emitter, which makes U-233 difficult to handle. Methods to limit the content of U-232 are expensive.

Uranium-233 has a critical mass much less than U-235 and is comparable to plutonium in terms of weapons-usability. Between 1955 and 1968 several nuclear weapons test were conducted using uranium-233 (Alvarez 2012).

In the United States about 1550 kg of U-233 was separated. Of this amount about 123 kg may be unaccounted for, enough for some 13 nuclear explosive devices. The radiation level from contaminants is not considered to be an adequate barrier to prevent a terrorist from making an improvised nuclear device. Storage of the US stockpile of U-233 is a safeguard, security and safety risk. The production of the stockpile also has left a disposal burden (Alvarez 2012).

How is the situation concerning U-233 in elsewhere in the world? Several countries are still involved in the development of a thorium-232/uranium-233 nuclear breeder system.

Plutonium

Plutonium is generated from uranium-238 (non-fissile) by neutron irradiation in nuclear reactors. The isotopic composition of the plutonium varies with the irradiation time in the reactor. At first the fissile plutonium-239 is formed and from this isotope heavier isotopes are formed by subsequent neutron captures: Pu-240 (non-fissile), Pu-241 (fissile) and Pu-242 (non-fissile). In nuclear fuel at low burnup little Pu-239 is transformed into heavier isotopes. The higher burnup of the fuel, the longer the stay time in de reactor and the more non-fissile heavy plutonium isotopes are generated.

Weapons-grade plutonium typically contains 93.6% Pu-239 (O'Connor 2003) and is produced in military reactors in nuclear fuel at low burn-up. Reactor-grade plutonium originates from spent fuel from civil power reactors and contains typically 71% fissile plutonium isotopes (Pu-239 + Pu-241). Contrary to assertions of the nuclear industry (WNA 2012b) reactor-grade plutonium is suitable for nuclear explosives, according to Barnaby 2005a and 2005b, Glaser 2005, Schneider 2007.

Plutonium has a much lower critical mass than uranium. The bare-sphere critical mass of weapons-grade plutonium is 11.5 kg (diameter 10.5 cm) and of reactor-grade plutonium 14.6 kg (diameter 11.5 cm). With a neutron reflector of 15 cm the figures are: 3.71 kg (7.20 cm), respectively 4.58 kg (7.72 cm), according to Glaser 2005.

In research reactors bomb-grade plutonium can be generated from uranium-238. In a reprocessing plant the plutonium can be separated from the uranium and fission products. If the process is aimed at the production of weapons-grade plutonium, the irradiation time of the nuclear fuel is kept short and the reprocessing of low burn-up spent fuel is not extremely demanding.

By beta decay, plutonium-241 transforms into americium-241; Am-241 is a strong gamma emitter, greatly increasing the gamma activity of the plutonium. Within a few years storage time, the concentration of Am-241 in reactor-grade plutonium builds up to a level the plutonium cannot be handled safely anymore. The decay product of Am-241 is neptunium-237 (see below). It is not clear what happens with the generated

Np-237 when plutonium is reprocessed to remove Am-241.
The global stockpile of reactor-grade plutonium, extracted from civil spent fuel, is estimated at more than 260 metric tonnes as of 31 December 2011 (IPFM 2013) and is stored in a number of facilities around the world. Evidently this material poses security and health risks when used in weapons or released into the public domain by accidents or terroristic actions. The global stockpile of weapons-grade plutonium was 234 metric tonnes as of January 2013.

Neptunium-237

During the fission process in the reactor the short-lived neptunium-239 isotope is formed from uranium-238 by neutron capture. Neptunium-239 decays with a half-life of 2.35 days to plutonium-239, a first-rate bomb material. In addition sizeable quantities of the long-lived isotope neptunium-237 (half-life 2.14 million years) are formed, mainly by neutron capture of uranium-235 and decay of americium-241. According to KfK 1983 roughly 400-700 g Np-237 per metric ton spent fuel are formed, depending on the burnup of the nuclear fuel. Np-237 can be separated by chemically means from the other elements in spent fuel, due to its specific chemical properties: it is a separate chemical element. After a cooling period of less than a year Np-237 is the only neptunium isotope remaining in spent fuel. Consequently it is possible to obtain a pure fissile material from spent fuel just by chemical means, without enrichment.

Neptunium-237 is fissile and can be used to produce a nuclear explosive device. Its critical mass is comparable to that of uranium-235. One or more nuclear weapon states may have tested a nuclear explosive using Np-237. Historically, neptunium 237 has been separated by the nuclear weapon states in only small quantities, principally for non-explosive uses, as target material for plutonium-238 production. Pu-238 can be used as neutron initiator of nuclear weapons.
By the end of 1997, the world inventory of neptunium and americium was estimated to exceed 80 metric tonnes, or enough for more than 2,000 nuclear weapons, and the amount is growing at a rate of as many as 10 tonnes per year. If actinide separation becomes routine, inventories of separated neptunium-237 and americium will escalate (ISIS 1999).

Americium

According to KfK 1983 about 120 g americium isotopes per metric ton spent fuel are formed at a burnup 33 GWe.day/Mg; at higher burnups the yield is proportionally larger. Americium has to be separated from plutonium and uranium after reprocessing, for reason of the high radioactivity of the americium isotopes and their unfavorable nuclear properties as reactor fuel. Assuming the isotope Am-242 (half-life 16 h) has already decayed to Cm-242, the main isotopes of americium in spent fuel are Am-241, Am-242m and Am-243. Just like neptunium, americium can be separated by chemically means from the other elements in spent fuel, due to its specific chemical properties.

All americium isotopes are fissile and can be used to produce a nuclear explosive device, so it is possible to obtain undiluted bomb material from spent fuel just by chemical means. Estimates of the bare-sphere critical mass of the americium isotopes vary from 9-150 kg. However, under special conditions the critical mass of Am-242m may be as low as 7 grams, according to Ronen et al. 2000.
Historically, americium has been separated by the nuclear weapon states in only small quantities, principally for non-explosive uses: for smoke detectors, neutron generators, and research activities. During reprocessing of spent fuel americium is usually discarded in the high-level waste streams.
The world inventory of Am-241 at the end of 1997 is estimated at some 45 tonnes and is growing by about 4 tonnes/year. This amount of Am-241 is the result of the decay of plutonium-241. In nuclear weapon programs

and civil plutonium recycle programs, americium-241 is separated from aging plutonium to purify it and reduce the material handling problems caused by americium's radioactive emissions (ISIS 1999). ISIS estimates the worldwide separation of americium at some 100 kg/yr.

2 Nuclear terrorism

Threats

Risks of nuclear terrorism are increasing as growing amounts of mobile radioactive materials come into existence. Two main fields of concern are:

- Terroristic nuclear nuclear explosives fabricated from stolen HEU, uranium-233, plutonium, neptunium and/or americium, use of dirty bombs.
- Terroristic attacks using conventional explosives on nuclear facilities with large radioactive inventories leading to large scale dispersion of radioactive materials. Vulnerable in this respect are nuclear power plants, spent fuel storage facilities and reprocessing plants, This topic will be addressed in Chapter 11.

Various sub-national groups have already demonstrated interest in weapons of mass destruction, including nuclear explosives. The detection of small quantities of bomb-usable material is a very major challenge (Schneider 2007). The 6 kg of plutonium contained in the Nagasaki bomb would fit in a soft drink can.

MOX fuel

MOX is the acronym of Mixed OXide fuel, nuclear fuel with plutonium instead of U-235. MOX fuel is relatively little radioactive and can be handled without specialized equipment. . A terrorist group would have little difficulty in making a crude atomic bomb from MOX fuel. Separating uranium dioxide and plutonium dioxide from MOX fuel can be done using straightforward chemistry. Converting the plutonium dioxide into plutonium metal, and assembling the metal together with conventional explosives to produce a crude nuclear explosive do not require materials from special suppliers. The information required to carry out these operations is available in the open literature (Barnaby 2005a, Barnaby 2005b).

Nuclear weapons can be made from reactor-grade plutonium, as pointed out above, although those made using weapon-grade plutonium are more effective. The USA and UK exploded devices based on reactor-grade plutonium in 1956 and in the 1960s. A good nuclear weapons designer could construct a nuclear weapon from 4-5 kg of reactor-grade plutonium. Less reliability or a less predictable explosive yield than a military weapon would not be a problem for a terrorist group planning an attack in the center of a large town. This is the reason why so many scientists all over the world are strongly opposing reprocessing of spent fuel and the use of MOX fuel in civilian reactors.

Safeguards of plutonium

The safeguarding agencies claim that a commercial plutonium reprocessing plant can be safeguarded with effectiveness of about 99%. This means that, even under the most optimistic assessments, at least 1% of the plutonium throughput will be unaccounted for. Some independent experts estimate that in practice a more realistic figure for the effectiveness is 95% and that at least 5% of the plutonium throughput will be unaccounted for (Barnaby 2005a, Barnaby 2005b).
What do these figures imply? A plant reprocessing 800 metric tonnes spent fuel a year and producing about 8000 kg plutonium a year, for example the Japanese Rokkasho-Mura plant, would have a potential 'material

unaccounted for' (MUF) of 80 kg (1%) to 400 (5%) kg plutonium a year. Measurement of the exact quantities of plutonium entering the reprocessing plant is virtually impossible, for various reasons. The operators of the reprocessing plant will be uncertain about the precise amount of plutonium produced in the plant.

In 2005 a large leak (83 m^3) of a liquor containing dissolved spent fuel at the THORP (THermal Oxide Reprocessing Plant) reprocessing plant at Sellafield in the United Kingdom went undetected for more than eight months. The leaked solution contained some 19 metric tonnes of uranium and 190 kg of plutonium and minor actinides. The fluids collected in a secondary containment. The fact that a shortfall in the amount of plutonium, enough for some 30 nuclear bombs, did not arouse concern for so many months, suggests that the theft of a significant amount of plutonium could also go undetected (Gronlund et al. 2007).

Application of plutonium from civil reprocessing plants as fuel in commercial nuclear power plants implies storage of large quantities of separated plutonium at various locations and frequent transports of plutonium and of plutonium-containing nuclear fuel (MOX fuel) by truck, or by ship. France is the country with the most extensive civil plutonium economy. The plutonium has to be shipped from the reprocessing plant at La Hague to the MOX fuel fabrication facilities at Marcoule and Cadarache. The fresh MOX fuel then is shipped to the nuclear power plants. The irradiated MOX fuel elements are either stored at the sites of the power plants or returned to the reprocessing plant. Each shipment, containing some 150 kg of separated plutonium or 250 kg plutonium in MOX fuel (WISE 2003), rolls about twice a week over the public roads and streets of France. Unirradiated MOX fuel is at its most vulnerable during transportation and risks of sabotage and hijacking must be considered seriously.

Japanese spent nuclear fuel has been transported from Japan to Sellafield in the UK for reprocessing, and the recovered plutonium has been transported back to Japan. Every transport of nuclear material enhances the risk of dispersion of radioactive material into the biosphere, by accident or terroristic actions.

Storage and transport of MOX fuel assemblies on the scale envisaged by the nuclear industry – both Generation III and Generation IV reactors will rely on plutonium recycling – will be extremely difficult to safeguard. The risk of diversion or theft of MOX fuel pellets or unirradiated fuel assemblies by personnel within the industry or by armed and organized terrorist groups is a dreadful possibility.

Safeguards of HEU and uranium-233

Highly enriched uranium (HEU) is not only used to fabricate nuclear weapons but it is also used in ship reactors and research reactors all over the world. Although the main part of the research reactors have been modified for low enriched uranium (LEU), still more than 100 are using HEU. That implies that there are stockpiles of HEU at may places and that transports are occurring frequently.
Under the terms of the Megatons to Megawatts program Russia has 500 metric tonnes of bomb-grade uranium diluted to LEU and exported to the USA. The program started in 1993 and ended 31 December 2013. Are all HEU quantities to be down blended accounted for?

The safeguard conditions of uranium-233 are not very clear. Regarding the situation in the USA Alvarez 2012 states:

> Our nuclear facilities may have done a poor job of keeping track of this dangerous material. Now, the Department of Energy has indicated it plans to waive safety requirements to dispose of it. But if the U.S. government makes a mess, they should clean it up. All uranium-233 should be accounted for, stored safely, and disposed of safely.

Safeguards of neptunium and americium

As pointed out in the previous section neptunium-237 and americium can be used to fabricate nuclear explosives. A principal concern is that a civilian reprocessing facility or a waste treatment facility in full compliance with its safeguard obligations could extract neptunium or americium that would not be under any international inspections. In essence, a non-weapons state could accumulate significant quantities of separated nuclear explosive materials outside IAEA verification (ISIS 1999).

Neptunium and americium are outside international controls — except for those controls included as part of the Wassenaar Arrangement for neptunium 237. In 1999 a voluntary monitoring scheme was approved by the Board of Governors of the IAEA regarding separated neptunium and americium. In its Safeguard Statement for 2011 (IAEA es2011) the IAEA states that it has received information from five States (Australia, France, Japan, Norway and the UK) about separated neptunium and americium and concludes:

> By the end of 2011, evaluation of the information that had been obtained under the monitoring scheme and from open and other sources had not indicated any issue of proliferation concern.

In its Safeguard Statement for 2006 (IAEA es2006) the IAEA states:

> The Secretariat continued to experience difficulties in obtaining information directly from States under the monitoring scheme approved by the Board of Governors in 1999 regarding separated neptunium and americium. More consistent reporting by States in this regard would improve the Agency´s ability to assess the quantities of separated neptunium and americium and the associated proliferation risk.

Obviously the international safeguarding system for neptunium and americium is far from watertight.

Dirty bomb

A dirty bomb is understood to be a conventional explosive used to disperse an amount of any hazardous radioactive material. Even without a nuclear explosion the dispersion of several kilograms of plutonium, americium or another highly radioactive material over a town by a small plane could have disastrous consequences.

3 Illicit trafficking and theft

Failing nuclear supervision

When the government of a state collapses, due to a take-over or other causes, a temporary lack of authority may initiate a lack of supervision on nuclear materials. Such a situation arose, for example, at the time of the dissolution of the former Soviet Union in 1991. Until the late 1980s nobody could imagine that such a far-reaching event could ever happen. There are many states in the world employing nuclear technology and a radical political change initiating a short vacuum of power on nuclear matters is conceivable. During such a period a nuclear disaster might happen, but theft of fissile material is also conceivable.

There is an identified black market for nuclear materials, including plutonium and highly enriched uranium. According to US Intelligence services, significant amounts of Russian nuclear materials are not accounted for (Schneider 2007).

Uncontrollable transports of nuclear materials

The nuclear industry uses large masses of expensive high-grade metals, alloys and other materials. After replacement of equipment or dismantling of nuclear facilities these materials may enter the market as used materials. Who controls the sorting of radioactive from non-radioactive scrap? Who safeguards the batches of high-value scrap which is not released for unrestricted use? Illegal trade, smuggling and criminality are already worrisome at this moment. Often pulses of radioactivity are observed in the flue gases of metal smelters and recycling plants of special materials; the sources of this radioactivity are called orphan sources.

Radioactive materials and components can be smuggled out of a port or country relatively easily (*Nature*, 4 March 2010, pp 26-27). Detectors, if present at all, have limited detection capabilities. Detection of many radionuclides in scrap metal or concrete rubble is very difficult if alpha emitters or low-energy beta-emitters are involved; low-energy gamma emitters may escape detection as well (NCRP-141 2002). The absence of easily detectable radionuclides, such as the γ-emitting radionuclides cesium-137 and cobalt-60, in no way indicates the absence of other dangerous radionuclides. So, when scrap metal or rubble is cleared for unrestricted use after superficial screening with a γ-radiation detector, how sure we are that all nuclides present in the materials have been measured and accounted for? It is relatively easy to shield radiation sources in a container from detection by non-radioactive scrap. In addition the human factor may play a part. How reliable are the inspectors?

Do the inspectors have sufficient means at their disposal to be able to detect all illegal transports, some of which may contain very dangerous materials? The International Atomic Energy Agency (IAEA) has to maintain a verification system that should allow the detection of undeclared activities at about 900 facilities in some 70 countries. However, considering its responsibilities, the IAEA has been notoriously underfunded for many years. The IAEA's entire safeguards budget is hardly more than € 100 million, about a third of the budget of the Vienna police department.
The EURATOM safeguards inspection efforts are on a continuous decline while the amount of nuclear materials under control has increased steadily (e.g. plutonium tripled). The Commission spends about € 13 million per year on safeguards. The EURATOM safeguards budget corresponds to about half of the annual budget of the international industry lobby organisation Nuclear Energy Institute (NEI). The number of inspection days is continuously decreasing (Schneider 2007).

Illegal dumping at sea

Up until 1993 large amounts of radioactive waste have been dumped at sea, including discarded ship reactors. A 1993 amendment to the London Dumping Convention halted the ocean disposal of all radioactive waste, officially. From 1979 on ships loaded with wastes have been wrecked under questionable circumstances in the Mediterranean at an increasing rate, Twenty of these wrecks are considered extremely suspicious with regard to radioactive waste. Serious engagement by magistrates and politicians to investigate the wrecks and their cargo has been lacking (*Scientific American*, February 2010, p 8-9). How is the situation elsewhere at the world's seas?
Additional hazards are introduced by 'commercial' waste handling by private corporations: corruption can easily occur and is hard to detect.

4 Nuclear security and reprocessing of spent fuel

Separation of fissile materials

From the previous sections it follows that a considerable part of nuclear security problems concerning fissile materials suitable to make crude nuclear explosives – plutonium, neptunium and americium – originate from one source: reprocessing of civil spent fuel. In addition uranium-233 is recovered by reprocessing from special thorium-uranium reactors.
Do the benefits of reprocessing outweigh the security and health risks it generates plus the costs of safeguarding the separated dangerous materials?
Without reprocessing the only way to acquire fissile bomb material would be enrichment of uranium.

In Europe two reprocessing plants are operating: one at Sellafield in the United Kingdom and the other at La Hague in France. In 1977 President Jimmy Carter banned the reprocessing of commercial reactor spent nuclear fuel in the USA. The key issue driving this policy was the serious threat of nuclear weapons proliferation by diversion of plutonium from the civilian fuel cycle, and to encourage other nations to follow the US lead. President Reagan lifted the ban in 1981, but did not provide the substantial subsidy that would have been necessary to start up commercial reprocessing. Up until this moment no civil reprocessing occurs in the USA.

Roots of reprocessing

Reprocessing was developed in the early days of the nuclear age to produce plutonium from uranium for atomic weapons. In the 1960s and 1970s commercial applications of reprocessing technology were developed, when de breeder concept came into the picture. Main purpose of the civil reprocessing plants at La Hague in France and Sellafield in Great Brittain was to get the plutonium from spent fuel from conventional nuclear power plants with light-water reactors (LWRs) for fuelling fast breeder reactors (FBR's) and to recycle the unused uranium.
The nuclear industry promised (and is still promising) that a closed-cycle reactor system (breeder) could fission 100 times more nuclei present in natural uranium, and consequently generate 100 times more energy from 1 kg uranium, than the conventional once-through system based on light-water reactors (LWRs). France (*'tout électrique, tout nucléaire'*) and the UK (*'too cheap to meter'*) embarked at the time on the materialization of the breeder concept, expecting that this could make their energy supply largely independent of fossil fuels.

However, realixation of the breeder cycle failed after decades of research and development in six or seven countries and despite investments of roughly €100bn. The breeder concept turned out to be implicitly flawed, based on unfeasible assumptions:

- availability of perfect materials
- technical systems with 100% predictable properties and behavior across decades
- 100% perfect separation of a mixture of a large number of different chemical species into pure fractions.

None of these conditions is possible, as a consequence of the Second Law of thermodynamics. This observation is also valid for the proposed partitioning & transmutation (P&T) system.

Security issues of the breeder and P&T cycles

If a breeder system were to come into operation, very large amounts of separated plutonium would be circulating in the cycle of breeder reactors, reprocessing plant and fuel fabrication plant. This would raise severe nuclear security problems. What's more the breeder cycle would generate much more high-level radioactive waste than conventional nuclear power stations and would discharge massive amounts of radioactive materials into the environment. These discharges are an unavoidable byproduct of reprocessing

Operating the P&T cycle would raise above mentioned security problems to much greater extent than the breeder cycle, because the P&T cycle would also circulate considerable amounts of separated actinides including neptunium and americium, in addition to the separated plutonium.
Fortunately the breeder and P&T concepts can only exist in cyberspace.

Benefits of reprocessing

After the breeder concept, and consequently the P&T concept, proved to be technically unfeasible in the 1990s, reprocessing became essentially superfluous. Because of the very high investments of a reprocessing plant (counted in tens of billions of euros), the nuclear industry in France and the UK looked for other 'markets'. Now the *raison d'être* of reprocessing is said to be:

- Volume reduction of high-level radioactive waste.
- Recovery of the unused uranium from spent fuel for recycling in new nuclear fuel.
- Recovery of the plutonium from spent fuel for use in LWR's in MOX fuel and so increasing the retrievable energy content a given mass of uranium.

The first point is based on a fallacy: by reprocessing spent fuel the volume of radioactive waste increases enormously and, in addition, significant fractions of the radioactive fission products and actinides from spent fuel are discharged into the environment.
The second point is based on a questionable premise, as reprocessed uranium is difficult to handle, and fabrication of nuclear fuel from recycled uranium is very expensive. It needs a higher fissile content of plutonium or U-235 than fuel from natural uranium.
The third point again is based on a fallacy. Application of MOX fuel has a negative energy balance: the production of a given mass of MOX (comprising recovery of plutonium from spent fuel plus MOX fuel fabrication) requires more energy than can be produced from that mass if all industrial processes from cradle to grave are accounted for. Moreover the use of MOX fuel in LWRs introduces serious terroristic threats, as pointed out above.

Keep spent fuel elements intact

Reprocessing of spent fuel is a superfluous, extremely costly and exceedingly polluting technology, raising severe security problems. These security problems can be avoided by keeping the spent fuel elements from nuclear power stations intact. In the elements all dangerous fissile and radioactive materials generated in the fission process are compacted in the smallest possible volume. Safe disposal of intact fuel elements in a geologic repository is the least hazardous way of dealing with this dangerous material and will require the least effort and financial investments.
Spent fuel is so highly radioactive that a person at a distance of a few meters from an unshielded spent fuel element would contract a lethal dose within minutes.

PART **B** SECURITY AND CIVIL NUCLEAR POWER

5 Theory versus practice

Limited scope

Security and safety are terms with different connotations in different contexts. The nuclear industry claims that nuclear power is safe with safe nuclear reactors. In their view the chance of a major reactor accident, involving a core meltdown (the worst case scenario), is one in the several millions of reactor-years.
The present world reactor fleet encompasses about 400 reactors. A chance of one major accident per million reactor-years would mean that a major accident could be expected once every 2500 calendar years (1 million divided by 400). Negligible compared to other risks, posed by other events in the society, as stated by the nuclear industry.
Empirical evidence proves the results of the reactor safety studies to be of little practical meaning. During the past decades three major reactor core meltdowns occurred: Three Miles Island (1979), Chernobyl (1986) and Fukushima (2011), an occurrence of once every 10-20 years, not counting other disasters in the former Soviet Union. This empirical fact is still invisible in the official publications of the nuclear industry concerning nuclear safety.

The claims of safe reactors by the nuclear industry are based on a small number of theoretical model studies, not on empirical data or on 'preflight testing'. In addition it is a fallacy to state that nuclear power is safe when the reactors are 'safe' (however defined). Firstly, there are many other potential sources of large-scale accidents. Secondly, inherently safe nuclear reactors and other nuclear installations are inherently impossible, as will be explained in section 9.

Another aspect of the theoretical basis of the security culture in the nuclear industry is its reliance on computer models. Each computer model has two kinds of limitations: inherent limitations and choice limitations. Inherent limitations follow from the fact that each model is by definition a simplified presentation of the reality. Choice limitations originate from the choices of parameters and variables and their values incorporated in the model.
Well-established regulations on paper are seen as the best way to prevent large nuclear accidents, proliferation, terrorism, etcetera. Adequate inspections and surveillance and means to enforce the regulations get less attention from the nuclear industry. Fulfilment of the regulations is usually left to the operators of the nuclear facilities, for they are too costly to implement effectively on an international scale. Besides that, political complications often play a part.

Reactor safety studies of the Western nuclear industry

The first major study on reactor safety was the famous 'Rasmussen Report' WASH-1400 1975. This report has been updated in 1990 (NUREG-1150 1990) and is at present being updated in the State-of-the-Art Reactor Consequence Analyses (SOARCA) by the US Nuclear Regulatory Commission NRC. Up until today only LWRs (light-water reactors) in the USA have been analyzed. Internationally the results of the US nuclear safety studies seem to be adopted as standards for other safety studies.

The official safety studies are Probabilistic Risk Analyses (PRAs), which have a limited scope:
- the PRA methodology does not cover all kinds of events which can cause a severe reactor accident,
- ageing and other Second Law effects are hardly quantifiable and are not included,

- unpredictable human behavior cannot be quantified.

The limited significance of PRA studies is also discussed by Dorfman et al. 2013 and Hirsch 2006.

Only a fraction of the processes comprising the worldwide nuclear energy system turns out to be examined in detail, for the safety analyses focus on nuclear reactors, in particular light-water reactors from Western vendors. What do we know about other reactor types (gas-cooled reactors, heavy water reactors, liquid metal-cooled reactors) and, equally important, about reactors from vendors in Russia, China, India, Japan, and Korea?

In the US the Nuclear Regulatory Commission (NRC) is found to be highly reliant on information from licensee risk assessments. There are no PRA standards, no requirements for licensee's PRAs to be updated or accurate, and consequently the quality of the assessments varies considerably among licensees (NRC 2002). Another limitation of the official safety studies is the fact that the other processes comprising the nuclear chain are only marginally, or not at all, addressed.

Those other industrial processes of the nuclear chain are practically invisible to the public, but not less important with respect to security. The amounts of radioactivity present at a given location of one of the back-end processes may be greater than the inventory of an operating nuclear reactor.

6 Engineered safety

Narrow safety margins

No technical system is perfect. In every production plant at any moment something may go wrong: a leaking coupling, a stuck valve, a bad electric contact, or whatever. Generally such failures can be ironed out without interruption of the production process or without endangering the personnel. In a nuclear plant the risks are much larger than in conventional plants. A small spill, only a nuisance in a conventional plant, may have serious consequences in a nuclear plant. For that reason the quality control specifications for materials, control systems and personal in nuclear plants are considerably higher than in non-nuclear plants.

Narrow safety margins are not typical for applied nuclear technology, another field of narrow margins is manned space flight. The crashes of the American space shuttles Challenger (1986) and Columbia (2003) were caused by ostensibly minor technical imperfections. The launch vehicle of the Challenger exploded as a result of an O-ring that was too cold at launch. The Columbia broke up during reentry because some pieces of plastic insulation came off the fuel tank during launch and damaged a critical part of the heat shield of the spacecraft.

The crashes of the two space shuttles took the lives of their crews, 14 people. A similar technical failure in a nuclear power plant might take the lives of tens of thousands of people and the health of millions of people, as has been proved by the Chernobyl and Fukushima disasters.

High quality requirements

High quality specifications mean a high degree of predictability of the properties and behavior of materials and structures. The higher the specifications the lower the tolerance for random occurrences, for impurities in the materials and for deviation from the dimensional specifications of the structures. High quality standards can be met by stringent control during the production process and by a large input of useful energy, most of it embedded in materials, specialized equipment and education of highly skilled personnel. From the Second Law of thermodynamics it follows that the energy inputs exponentially increase with increasing

quality specifications of a given amount of material or piece of equipment.
Unrealistic faith in high-tech systems turns out to be based on some implicit assumptions:

- availability of perfect materials,
- 100% predictability of the properties and behavior of a technical system
- 100% perfect controllability of a system.

The latter assumption implies, among others, that human behavior is 100% predictable.
The first two assumptions are in conflict with the Second Law of thermodynamics. One of the consequences of the Second Law is that separation and purification processes never go to completion, so 100% pure materials and 100% reliability of constructions are impossible.

One of the conclusions of Paulitz 2012, in his analysis of the Fukushima accident is:

> Not to be underestimated is also the fact that every nuclear reactor has its own—albeit unlikely— "trigger event" or accident scenario for which there is simply no solution and, to all intents and purposes, the workforce is obliged to look on helplessly while the meltdown takes place.

Human factor

Even if the engineered safety measures of nuclear power worked according the design criteria, risks are introduced by the human factor. Routine tasks such as operation and maintenance are susceptible to errors, sloppiness, poorly educated personnel and incompetence. Any company and organization may have to deal with these factors, but in the nuclear industry the safety margins are small and the consequences may be disproportionally large and irreversible.
Problem identification and resolution programs – how plant owners find and fix safety problems – are often flawed or even dysfunctional. Violation of the Technical Specifications, part of the operating license issued by the NRC to the owner of each power reactor in the USA, is another problem Lochbaum 2004 observes. How is the situation in other countries?
Bad management, shortage of funds and of qualified personel, shifting priorities, matters of prestige and cognitive dissonance will lead to less than optimal control and consequently to enhancement of risks. Financial interests may entice people to make choices based on a belief in unproved technology or an unshakeable faith in security measures which seem perfect on paper but turn out to exist only in cyberspace, while arguing away the contra-indications.

7 Ageing of materials and structures

Second Law of thermodynamics

All materials and structures inevitably deteriorate over time due to a combination of spontaneous chemical and physical processes, a phenomenon usually called ageing. The rate of ageing of materials and components depends partly on the operating conditions. As a consequence of the Second Law of thermodynamics spontaneous processes are always degrading the quality of materials and structures. Common examples of such degrading processes are corrosion of metals, wear of moving components, weathering of concrete and quality loss in plastics. The degradation processes may be retarded by dedicated effort and investments of useful energy and materials, but never can be eliminated.
Ageing processes are generally difficult to detect because they usually occur on the microscopic level of the inner structure of materials. They frequently become apparent only after a component failure has occurred. Leakages or other signals cannot always be detected before a component, for example a pipe, catastrophically fails.

Important factors influencing the ageing processes of nuclear power plants and its components are:

- nuclear radiation (alpha, beta, gamma, neutrons)
- chemical processes
- thermal loads
- mechanical loads
- corrosive and abrasive processes
- combinations and interactions of above mentioned processes.

Thermal and mechanical loads can cause creep and cracking and so may clear the way for chemical processes. Corrosion comprises a gamut of physical and chemical processes. Nuclear radiation, especially neutron radiation, causes embrittlement of metals and accelerates other degrading mechanisms. Many materials and components in a nuclear power plant are exposed to high temperatures and pressure, to nuclear radiation, and most of them also to water and air.

Often changes in mechanical properties cannot be recognized by non-destructive examinations. Therefore it is difficult to get a reliable, conservative assessment of the actual state of materials. In the case of limited accessibility due to the layout of components and/or high radiation levels not all components can be examined a full hundred percent. Therefore, it is necessary to rely on model calculations in order to determine the loads and their effects on materials. Not even the most complex calculations can cover all conceivable synergistic effects. With increasing age of plants, degrading mechanisms might occur which were not foreseen, or which have even been excluded from the models. As has been explained above, models always have their inherent limitations.

Concrete is also subject to ageing. Degrading mechanisms of concrete stuctures in the presence of nuclear radiation are largely unknown. Safety analyses are based on design material parameters. Weakening of structures over time cannot be included in a reliable way in the models and probabilistic risk assessment (PRA) studies, because most ageing mechanisms are not well understood and non-quantifiable factors may be also important. Weakening of concrete structures could have serious consequences in case of seismic events.

Electronic devices

In a nuclear power plant, many electronic devices are used. Temperature and radiation are the main factors leading to ageing. Additional degradation can occur due to humidity and chemical attacks. Because of the great variety of different devices and the complex ageing phenomena, which have not been systematically investigated so far, reliable lifetime estimates are very difficult. With increasing age of a plant, the reliability of electronic devices can thus be reduced while at the same time, safety margins in the whole system are decreasing (Hirsch et al. 2005).

Spent fuel

Obviously the degradation of the condition of spent fuel elements, during the time spent in interim storage after removal from the reactor, is no exception to the above observations. On the contrary, one might expect the ageing of spent fuel elements to occur faster than the materials and components of the nuclear power plant and of non-nuclear materials and structures, due to the elevated temperature of spent fuel, high pressure, the presence of dozens of different chemical species and the presence of energetic nuclear radiation.

8 Bathtub hazard function

Failure rates

The risks for catastrophic breakdown of technical devices, including nuclear reactors, change as the devices age, much like the risks for death by accident and illness change as people get older. There are three distinct stages in the lifetime of a technical system or living organism:

- the break-in phase, also called the burn-in phase or the infant mortality phase,
- the middle life phase, also called the useful life,
- the wear-out phase.

The risk profile, the failure rate as a function of time, for these three phases curves like a bathtub (see Figure 1). The bathtub curve is drawn from statistical data about lifetimes of both living and nonliving things, such as cars, cats or nuclear reactors (Sheldon 2009, Stancliff et al. 2006, various classical textbooks on this subject).

Applied to technical devices only, the bathtub curve may be considered to be the sum of three types of failure rates:

- Early life ('infant mortality') failures, caused by bad design, defective manufacturing, material imperfections, faulty installation, unanticipated interactions, poor workmanship imperfect maintenance and ineffective operation. The failure rate of this type decreases with time. The steepness of this curve depends on factors such as the amount of 'pre-flight' testing and the effectiveness of the quality control during manufacturing.
- A constant rate of random failures during working life, caused by accidents and random events. The height of this rate depends on, among other things, the quality of the materials, of the design and the professionalism of the operators. In principle the random failure rate does not change with time.
- Wear-out failures, caused by ageing, deterioration of materials, etcetera. This rate increases with time. Wear-out failures are typically the consequences of Second Law phenomena.

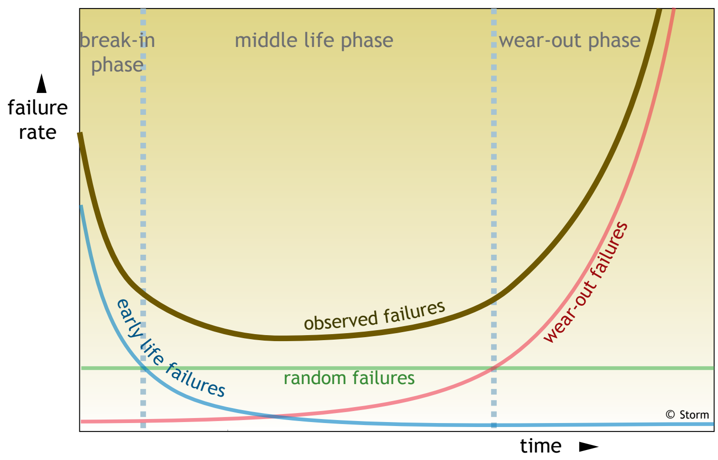

Figure 1

Bathtub hazard curve, as the sum of three types of failure rates. The bathtub curve is valid for technical devices, including nuclear installations, as well as for living organisms.

Preflight testing

The concepts behind the bathtub curve are playing an important part in space technology. The reliability and predictability of the behavior of each component of a spacecraft or launch vehicle has to be extremely high to achieve a specified reliability of the complex assembly as a whole: the spacecraft or launch vehicle. Extensive testing and screening procedures are applied to pass all components and assemblies through the break-in phase and to eliminate design flaws, manufacturing defects, etcetera. Functional flexibility by redundancy in the design of the spacecraft systems and very high quality standards minimalize the occurrence of random failures and postpone the wear-out failures. Exhaustive screening and pre-flight testing and stringent quality control enables a spacecraft to function unattended for a decade or longer. The effort needed to achieve such a level of reliability is exceedingly large, a direct consequence of the Second law. Large efforts mean high input of energy, materials and human resources, and consequently high financial cost.

Bathtub function and nuclear technology

In commercial nuclear technology no 'pre-flight' testing occurs. A nuclear power plant is assembled at the location chosen by the utility that will operate the plant. Design flaws and manufacturing defects are uncovered during construction and the first several years of operation of the nuclear power plant: the burn-in phase. Historical evidence indicates the burn-in phase of nuclear power plants to be several years. Major failures of nuclear reactors, including Three Mile Island 2 and Chernobyl, occurred during the burn-in phase.

As Lochbaum 2004 put it, describing the situation in the USA:

> The nuclear power industry's chronic quality control problems during design and construction are legendary, as is the NRC's (Nuclear Regulatory Commission) consistent inability to do anything about it.

How is the situation in other countries?

It is exactly these factors contributing to the burn-in phase failures that are one of the causes of massive cost overruns of nuclear power plants and other large technological energy projects, as analyzed by the RAND Corporation, (RAND 1981 and RAND 1979). Recent examples of the habit of the nuclear industry, building before testing, are the troubled construction of the European Pressurized Reactors (EPR) at Olkiluoto in Finland and at Flamanville in France, causing dramatic cost overruns and time delays.
Economic pressure on reactor safety will be addressed in Part C of this report.

No human-made structure can be made absolutely fail-safe for an operating lifetime of decades. Accidents and random events are unpredictable by definition. The functionality of materials and structures predictably declines with time by cracking, wear, corrosion and other Second Law phenomena. The rate of wear-out failures predictably increases with time. These observations lead to one conclusion:

Inherently safe nuclear power is inherently impossible.

9 Preventable yet unavoidable accidents

The official Japanese investigators called the Fukushima disaster a 'man-made accident' and a 'preventable accident' (NAIIC 2012a). Obviously all accidents involving man-made objects and technical installations are man-made. At issue is the question: are 'man-made' accidents always preventable? Each particular accident may seem preventable, for in principle nearly all failure modes are preventable. However, the occurrence of 'man-made' acidents in general is not preventable. Accidents will happen, that is one of the consequences of the Second Law. We just cannot predict where and when and which failure mode will occur.

The sinking of the Titanic in 1912, the chemical disaster at Bhopal in 1984 and the crashes of the US space shuttles Challenger (1986) and Columbia (2003) are some well-known examples of non-nuclear preventable accidents. Preventable and man-made accidents, they happened, although nobody wished them to happen. If technical installations with narrow safety margins are involved, such as nuclear reactors and spacecraft, the consequences of a minor mishap could be disastrous.
Chairman Kiyoshi Kurokawa of the official commission that investigated the Fukushima disaster seems to endorse this viewpoint in his Preface to the final report NAIIC 2012b:

> The parties involved in this accident had forgotten some fundamental principles: "accidents will occur," "machinery will break down," and "humans will err." They minimized the possibility of accidents to the point of denying it, and in doing so they lost their humility in the face of reality.

To the nuclear industry the qualifications 'preventable' and 'man-made' seem to suggest that nuclear power in itself is safe and that accidents like the Fukushima disaster could be prevented by writing better regulations; ergo: continuation of the 'business-as-usual' mode. Apparently the Chernobyl and Fukushima disasters were not deemed reason to reconsider the indispensability and benefits of nuclear power versus its costs in the sense of economic damage and the harm to the health of millions of people.
As pointed out above the chances of large-scale nuclear accidents are rising with time for a number of reasons, despite efforts to make nuclear power safer. Economic factors might prove the highest risk factor (see Part C of this report).

10 Mechanisms of large-scale nuclear accidents

Potential sites

In principle each site holding a substantial amount of spent nuclear fuel, or equivalent amounts of radionuclides, is a potential source of large-scale dispersion of radioactive materials:

- nuclear reactors
- spent fuel cooling pools
- reprocessing plants.

An operating reactor at an electric power of 1 GWe produces each year an amount of radioactivity equivalent to about 1000 exploded nuclear bombs of 15 kilotons (Hiroshima bomb). Spent fuel cooling pools at reactor sites may contain spent fuel from a number of years, say, 1000-10 000 nuclear bomb equivalents. Off-site cooling pools may contain much more: 10 000-100 000 nuclear bomb equivalents. A reprocessing plant may contain the radioactive contents of hundreds of reactor cores: 100 000-1 000 000 nuclear bomb equivalents of radioactive materials, partly as spent fuel, waiting in cooling pools for processing, partly as conditioned and unconditioned radioactive wastes.

The area within a radius of 30 km from each nuclear power plant is a potential evacuation zone in case of a severe accident at the power plant. Figure 2 shows the areas that would be directly affected by large-scale accidents at reactors and reprocessing plants in Europe. The map shows that nearly the entire inhabited area of Europe lies within the 300 km zones around nuclear power plants, which could become heavily contaminated in case of an accident. These zones are based on models. The maps of the contaminated areas after the Chernobyl and Fukushima disasters show that heavy contamination might reach far beyond the 300 km zone.

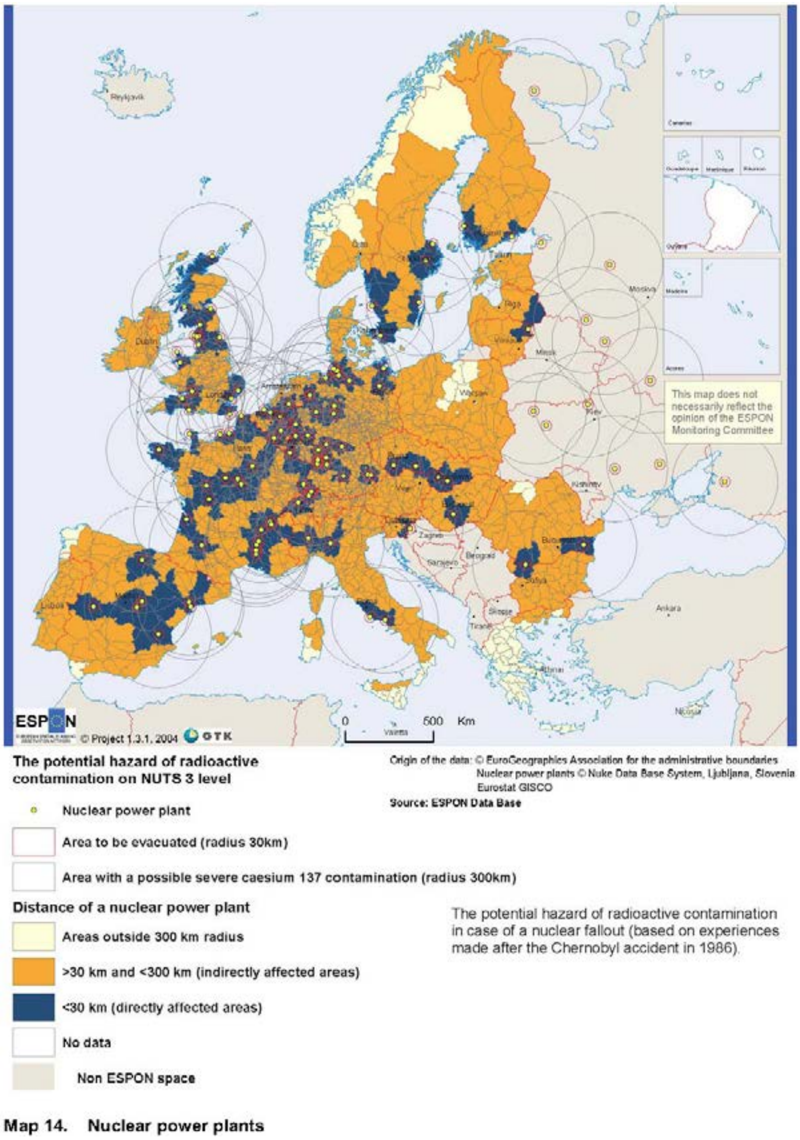

Figure 2

Chart with the nuclear power plants of Europe. The darkest colored areas are within 30 km of an NPP and are the areas to be evacuated in case of an accident releasing nuclear fuel. The risks posed by accidents involving the interim storage of spent fuel might be greater than reactor accidents. Most interim storage facilities are located at the reactor site. Source: ESPON 2006.

Mechanisms

Various mechanisms are conceivable for dispersion of large quantities of radioactivity from spent nuclear fuel into the environment.

Violent releases resulting from meltdown of nuclear fuel, fires and explosions. Such events in turn might result from a loss-of-coolant accident (LOCA). Used nuclear fuel generates much residual heat for decades, due to the radioactive decay of radionuclides. If not cooled actively, spent fuel elements will melt. The Zircaloy (98,5% zirconium) cladding of the fuel elements contains zirconium hydride, which is highly flammable at elevated temperatures. In case of LOCA the spent fuel rapidly heats up and the cladding catches fire, accelerating the meltdown of the fuel. At high temperatures zirconium metal reacts with residual water, generating hydrogen, and hydrogen explosions are unavoidable. As a result of these violent events the radionuclides from the spent fuel will be dispersed into the air and water, including the non-volatile radionuclides as aerosols.

In case of a LOCA in an operating reactor the meltdown and coupled events would occur in a matter of minutes. If a LOCA hits a spent fuel cooling pool, the same events will occur at a slower pace. Both events happened at the Fukushima Daiichi nuclear power plant.

Figure 3

Explosion at the spent fuel cooling pool of reactor 3 at the Fukushima Daiichi plant on March 14, 2011. As a result of the breakdown of the cooling of the pool, the spent fuel partially melted and reacted with the remaining water. The hydrogen generated by this reaction exploded, initiating a criticality incident in the (partially) molten nuclear fuel.

Causes and triggers

A loss-of-coolant accident can be triggered by various events and causes, such as ageing of materials and construction, human error (e.g. bad maintenance), natural disasters (floods, earth quakes), accidents, terrorisms, war acts, or infection of the electronic control system by a computer virus or a computer worm, such as Stuxnet (see also Hirsch et al 2005).

Criticality incidents

An additional hazard is the possibility of criticality incidents with the spent fuel. If a large mass of spent fuel elements is compacted sufficiently, for instance by a meltdown and/or explosion, the molten fuel could attain criticality and an uncontrolled fission process would start. Likely this occurred several times at the cripled reactors of the Fukushima Daiichi power plant and when the hydrogen explosion occurred at reactor 3. At several occasions after the meltdown the release of short-lived fission products has been observed. Criticality events also happed after the explosions and meltdown of the Chernobyl reactor.

Radiolysis of water

Radiolysis of water may entail a long-term hazard. If water enters the radiation shield of dry casks containing spent fuel, hydrogen and oxygen will be formed from the interaction of nuclear radiation with water (vapor or liquid) and hydrogen explosions become possible. In combination with other degrading mechanisms of spent fuel and its containers such explosions could initiate major accidents.

During storage of spent fuel in cooling pools radiolysis of water constantly occurs. Under normal conditions the hydrogen is removed from the air by the ventilation system. If that fails a hydrogen explosion may become unavoidable.
Radiolysis of water raises a concern regarding the storage tanks of highly radioactive reprocessing waste liquids. If not cooled and ventilated adequately, such storage tanks could explode.

11 Vulnerability of nuclear installations

Mass casualty attacks

Current trends suggest an increasing risks of future terroristic actions aimed at mass destruction and social disruption; as Frank Barnaby (Barnaby 2003) put it:

> To discuss future terrorism it is useful and important to distinguish between the 'old' terrorists, likely to continue with 'business as usual', using conventional weapons to 'kill one and frighten thousands', and the 'new terrorists', aiming to 'kill thousands to frighten the hemisphere' with weapons of mass destruction.
>
> . . .
>
> Whereas secular terrorists are likely to exercise constraint, and to avoid killing many when killing a few suits their purposes, religious fundamentalists are unlikely to feel any moral constraint about killing very large numbers of people.

As pointed out in the previous chapter the most vulnerable nuclear facilities are nuclear power plants, interim storage facilities of spent fuel and reprocessing plants, because of the presence of very large amounts of highly radioactive materials. These facilities are not able to withstand the crash of a heavy aircraft, with a large load of kerosene. After 9/11 intentional aircrafr crashes on nuclear installations are well conceivable.
A detailed analysis of the physical aspects of the potential impact of fuelled aircraft is given by Large & Schneider 2002.

Attacks with conventional weapons on one of the mentioned highly hazardous nuclear facilities could initiate severe large-scale accidents; Hirsch et al. 2005 describe a number of conceivable attack scenarios.
If an attack results in a power loss, including the emergency power generators, a loss of coolant resulting in a reactor core meltdown seems unevitable.
Reprocessing plants contain in their waste storage tanks very large amounts of radioactive materials, chiefly in easily dispersible condition, such as unconditioned liquid and solid wastes. In addition substantial amounts of plutonium, neptunium and americium are stored in reprocessing plants. A fire in such a storage facility might have disastrous consequences, by dispersion of these highly radiotoxic materials over vast area's.
Another vulnerable component of the nuclear chain are spent fuel cooling pools. Meltdown of nuclear fuel could occur in the cooling pools of nuclear power plants and reprocessing plants. If the cooling of the high-level waste tanks of a reprocessing plant fails, they might boil dry and explosions will disperse immense amounts of radioactivity into the environment.
Dry casks containing spent fuel are also vulnerable to terroristic attacks.

Armed conflicts

An armed conflict with conventional weapons has the potential to cause severe nuclear accidents, if nuclear power plants or storage facilities are hit by bombs and/or penetrating projectiles, intentionally or by accident. Although storage facilities are safeguarded, all are vulnerable to wartime acts. Even nuclear power

plants with heavy containment buildings are not able to withstand attacks with conventional weapons.
A forced shutdown of nuclear power plants of the adversary of a belligerent party may be an attractive option. Nuclear power plants are generally large units, 1000-1600 MWe, and by cutting out one or more of these large units the energy supply of the adversary, and with it its economy, is dealt a heavy blow. This can be done by cutting power to the grid, even without damaging the power plant itself. For these reasons nuclear power plants may be considered targets for terroristic actions as well. The historical trend of economic targeting by paramilitary groups looks worriesome (Rogers 2008).

If the emergency electricity generators were to fail or if the operating personnel were not able to function adequately, for whatever reason, a reactor meltdown could occur, as well as a meltdown of the spent fuel in the cooling pool.

Armed conflicts may seem a remote possibility in Western Europe and in the USA, but how about other nuclear countries in the world? The consequences of a severe nuclear accident do not stop at our borders. Chernobyl and Fukushima proved how far-reaching those consequences can be.

Natural disasters

Natural disasters, such as earthquakes and floods, could cause large-scale nuclear accidents, as Fukushima unfortunately has proved. Due to climate change the chances for severe weather and floods increase. The vulnerability of the current ageing fleet of nuclear power plants increases with time.

PART C NUCLEAR SECURITY AND ECONOMICS

12 Economic preferences versus security

The economic connection

Non-Proliferation Treaty

Investments in nuclear power plants, reprocessing plants and other nuclear facilities are exceedingly high. Not surprisingly the nuclear industry seeks new markets, to sell their products or technology to other countries, however questionable from a political point of view. In 1970 the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) entered into force. Since that date numerous violations of letter and spirit of the NPT, involving many countries, such as, USA, Canada, Russia, France and China (Schneider 2007). Do economic motives prevail over security risks?

MOX fuel

As explained in Part A, the use of plutonium in MOX fuel generates high risks of diversion, hijacking and theft of bomb-usable fissile material. From an energy point of view there are no physical arguments in favour of recycling plutonium in light-water reactors, for the energy balance of the use of MOX is negative. The recovery of plutonium by reprocessing spent fuel and the fabrication of the MOX fuel elements consume more energy than can be generated from the MOX fuel, if all processes from cradle to grave are included in the energy balance. Especially the decommissioning and dismantling of the reprocessing plant will require a massive investment of energy, materials and human effort (more details in Chapter 14).
So for what reason MOX is still used, despite the very serious security issues it raises? Just for short-term profit making, to generate some return on the extremely high investments of the reprocessing plants?

Independence

Nuclear security may easily become at odds with economic preferences if the required investments do not generate a return on investment in the short term. Safety measures are vulnerable to economic priorities and short-sighted choices: the standards, the quality control and the independence of inspections. The strained connections between economics and nuclear security is clearly expressed in the French Roussely report (Roussely 2010):

> 'La question du risque nucléaire acceptable, ou plus généralement du risque technologique acceptable, est un débat de société à part entière pour lequel la ou les réponses à donner sont naturellement du rôle du Politique. Force est néanmoins de constater que la notion même de compétitivité du nucléaire et l'hétérogénéite des règles de sûreté selon les Etats renforcent l'actualité de ce débat et la nécessité de préciser certaines exigences de sûreté. La seule logique raisonnable ne peut pas être une croissance continue des exigences de sûreté.'

In English translation:

> 'The question of what is an acceptable nuclear risk, or more generally an acceptable technological risk, is a debate that concerns the entire society and for which the answer(s) obviously belongs in the political domain. However, one must note that the concept itself of competitiveness of nuclear power and the heterogeneity of the security rules according to each country reinforce the relevance of this debate and the need to specify certain security requirements. The continued increase of security requirements cannot be the only reasonable rationale.'

Radiological protection recommendations

The International System of Radiological Protection that is used across Europe and worldwide is based on the recommendations of the International Commission on Radiological Protection ICRP and the

International Commission on Radiation Units and Measurements (ICRU), according to SCENIHR 2012. These recommendations are based on three fundamental, essentially economic, principles:

- justification
- optimization
- dose limitation.

The principles of justification and optimization apply universally to all three exposure categories defined by the ICRP, whereas dose limits apply only to planned exposure situations, except some medical exposure situations.

The main task of the ICRP seems to be the formulation of a legal framework for authorities and politicians on how to cope with liabilities which may arise by exposure of people to radiation and/or radioactive materials, see for example ICRP 103 2007 and ICRP 111 2009.

Life extension of nuclear power plants

De-regulation (liberalisation) of electricity markets has pushed nuclear utitlities to decrease safety-related investments and limit staff (Hirsch et al. 2005).

Extension of the operational lifetime of a nuclear power plant may be the single most important determinant of nuclear electricity production in the coming decades according to the IAEA, as quoted by Hirsch et al 2005. This trend is clearly grounded in economics: the cost of the currently operating reactors escalated during construction by a factor 2-5, so there is a strong incentive to extend the operational lifetime of the reactors beyond their intended design lifetime. New reactors are even more expensive; costs overruns are the rule in the nuclear industry.

Licensing procedures for lifetime extension are based on the as-designed quality of materials and structures. However, the reactors in question are now in the wear-out phase of the bathtub function, implying that the failure rate of components is increasing exponentially.

As the world's nuclear power plant population gets older, there are efforts to downplay the role of ageing, including conveniently narrowing the definition of ageing. There are ageing effects leading to gradual weakening of materials which may have no observable consequences during reactor operation, but which could lead to catastrophic failures of components and thus subsequent severe radioactive releases. Most notable among those is the embrittlement of the reactor pressure vessel, increasing the hazard of vessel bursting. Failure of the pressure vessel of a PWR or a BWR constitutes an accident beyond the design basis.

Relaxation of clearance standards

The high and continually escalating costs of waste management and disposal may provoke undesirable developments and hazardous situations. Standards and regulations may be relaxed to admit higher concentrations of radionuclides in materials for clearance, because of economic reasons. Clearance is the controlled release of materials into the public domain; once released the materials are no longer subject to regulation.

The International Atomic Energy Agency (IAEA) proposed to dilute radioactive materials with non-radioactive and to use concrete rubble as landfill or road paving (IAEA-293 1988). 'Weakly' radioactive steel scrap – however defined and measured – could be remelted with fresh steel and used for 'special purposes'. Reuse of 'low-activity' contaminated and/or activated steel and concrete by diluting it with fresh steel or concrete, as proposed by the IAEA, is very risky for several reasons:

- the unknown but potentially hazardous isotopic composition of the scrap and rubble
- the unknown biological behavior of the radionuclides
- problematic detection of a number of radionuclides .

- uncertainties with regard to standards, inspection and control
- the high risk of uncontrolled trade in radioactive materials.

Findings of the National Council of Radiation Protection and Measurements (NRCP-141 2002), concerning potentially radioactive scrap metals, are indicative of an urgent and problematic situation in the USA:

> 'There is an urgency to establish consistent national/international policies and standards.'

In Europe, with its many different countries, the situation is far more complex and probably more problematic. In case of the waste released by dismantling nuclear power plants and other nuclear facilities, it would be wise to avoid unconditioned waste shipments and trade of radioactive scrap metal and debris as much as possible by packing the materials at the source: the reactor or reprocessing plant being dismantled.

Regulations and quality control

What is the radioisotopic composition of any given radioactive component in the debris or scrap? Will that composition have been measured or will it be estimated based on models from the early 1970s? What is known about the biomedical activity of the radionuclides in the debris and scrap? Another problem is the difficulty in detection of a number of hazardous radionuclides.
In view of the large problems already existing with regard to illicit trafficking, great risks are looming here, even without relaxing the standards. Large volumes of debris and scrap that can be measured in thousands of tonnes, sometimes of high value on the free market, are released by decommissioning and dismantling of nuclear facilities.

If the handling and management of radioactive debris is left to private companies, profit seeking might easily prevail over safety and public health. Financial motives for short-term 'solutions' may be backed by financial constructions that place the liability for failures and mishaps on the customer, which in turn would place it on the taxpayer. Such financial constructions seem to be involved in the contracts for decommissioning and dismantling of the Sellafield reprocessing plant under the authority of the British Nuclear Decommissioning Authority (NDA 2006).

Relaxation of discharge standards

Economic arguments may also lead to relaxation of the standards for routine emissions of radioactive materials by nuclear installations. An example is the proposal of the US Environmental Protection Agency (EPA) to dramatically raise permissible release levels. The new standards permit public exposure to radiation levels vastly higher than EPA had previously deemed unacceptably dangerous (PEER 2009). EPA increased permissible public exposure to radiation in drinking water with factors of 1000 to 100 000 involving several fission products with short and long half-lives. In the most extreme case the new standard would permit radionuclide concentrations 7 million times more lax than permitted under the Safe Drinking Water Act. Other aspects of the new EPA proposal are lax cleanups and higher exposures to other sources, such as relaxed dirty bomb standards.
In view of the reliance on models within the nuclear industry and the ease with which models can be adapted to changing financial needs of the nuclear industry, any relaxation of standards should be based on verifiable empirical evidence.

How independent are the inspections?

Several incidents at nuclear power stations in the US during the past years point to reduced quality controls by official inspectors. In a number of countries the nuclear industry urges simplified and shortened licensing

procedures to speed up the construction of new nuclear build, with minimalization or even elimination of the participation by the local authorities and the public.
The independence of the controlling institutions may suffer under economic pressure. The above described relaxation of the exposure standards by the US EPA points in that direction. The Roussely report (Roussely 2010) calls for a reduction of the independence of the French Safety Authority ASN (Autorité de Sûreté Nucléaire), see quotes above. The decision process on nuclear power in France is controlled by the president and the Corps des Mines (a technocratic elite), effectively without the participation of the parliament (Schneider 2008).
What is the situation in other countries?

13 Consequences of severe nuclear accidents

Two faces of the IAEA

Communication between the nuclear world and the general public is dominated by the International Atomic Energy Agency (IAEA). The authoritative 'nuclear watchdog' IAEA has the promotion of nuclear power in its mission statement. Moreover, official publications of the IAEA have to be approved by all member states of the IAEA.
For these reasons it is a misconception to regard the IAEA as an independent scientific institute. One face of the IAEA is looking at the safeguards of nuclear materials and technology, the other face is looking at the promotion of nuclear technology and nuclear power.

Entanglement of interests

Information on nuclear matters to the public and politicians originates almost exclusively from institutions with vested interests in nuclear power, such as: IAEA, World Nuclear Association (WNA, the official representative of the Western nuclear industry), Nuclear Energy Institute (NEI) in the US, Areva, Electricité de France (EdF), the latter two being 90% state-owned in France. The views of the Nuclear Energy Agency (OECD-NEA) rely heavily on the IAEA and WNA. The IAEA plays a dominant role in the statements of the nuclear world concerning nuclear security and health effects of dispersion of radioactive materials into the human environment.

How independent are the reports on the consequences of radioactive contamination for the local inhabitants, for example after the disasters of Chernobyl and Fukushima?
According to an agreement between the International Atomic Energy Agency and the World Health Organization (UN Res. WHA12-40, 28 May 1959) the WHO cannot operate independently of the IAEA on nuclear matters, see also the preface of WHO 2013a. Bertell 2002 reports on the strong connections between IAEA and UNSCEAR and ICRP, the authorities who formulate the recommendations regarding allowable radiation doses.

Wide disparities

During the first decade after 1986 the IAEA, the WHO and the nuclear industry claimed that the death toll of the disaster at Chernobyl was 31, many years later it was raised to 'less than 50'. From a scientific viewpoint this assertion is highly questionable for two reasons. No fixed number of casualties resulting from a nuclear disaster can be established within months after the onset of the disaster, because radiation-induced lethal cancers and lethal non-cancer diseases manifest themselves after latency periods of years to decades.

Moreover, any number of casualties can only be determined, better: estimated, by means of extensive investigations of the whole affected population. The IAEA and WHO do not refer to any investigation of this kind. Apparently the IAEA and WHO attribute only the victims of deterministic effects, caused by exposure to very high doses of radiation, as victims of the Chernobyl disaster.

An independent assessment estimated the death toll world wide of the Chernobyl disaster at nearly one million people (Yablokov et al. 2010). This estimate is based on numerous publications from Russia, Belarus and Ukraine, which the IAEA and WHO did not include in their studies. In addition to the casualties there are innumerable people with incurable diseases and malformations following the disaster in 1986, all of whom are ignored by the IAEA and WHO without investigation. The findings of Yablokov et al. are broadly endorsed by the elaborate study of the German Affiliate of Nobel Prize winner International Physicians for the Prevention of Nuclear War (IPPNW) and of the Gesellschaft für Strahlenschutz (IPPNW 2011).

At present the nuclear industry is strongly downplaying the gravity of the Fukushima disaster, which is classified as 'non-catastrophic'. In the view of the nuclear industry the worst effects are economic losses, financial liabilities and less support for new nuclear power stations.

The long latency periods of anonymous cancers and genetic effects due to radiation and radioactive contamination give the nuclear industry the opportunity to downplay the effects and even to deny that radioactivity caused observed adverse health effects. Other factors are blamed as the cause of observed disorders, sometimes even psychosomatic factors: 'radiophobia', the fear of radiation. The WHO pays little attention to physical ill effects and much attention to 'mental health problems' and similar issues (WHO 2005):

> "Poverty", "lifestyle" diseases now rampant in the former Soviet Union and mental health problems pose a far greater threat to local communities than does radiation exposure.

and:

> Persistent myths and misperceptions about the threat of radiation have resulted in "paralyzing fatalism" among residents of affected areas.

The WHO does not mention non-cancerous diseases as possible ill effects caused by radioactive contamination, but attributes these effects to other factors. These statements are not proved by investigations or backed by scientific arguments. The study of IPPNW 2011 states:

> An inadmissible chain of argument is often applied: non-cancerous – therefore not induced by radiation – therefore not a result of Chernobyl – end of debate.

In one of its publications (WHO 2005), referring to the Chernobyl Forum in 2005 (see Chernobyl Forum 2008 and 2006), the WHO claimed to know the true scale of the Chernobyl accident. What is the 'true scale'? Are definitive answers possible within less then 20 years after the accident and without large-scale independent medical investigations during an appreciable number of years? Worse is the following quote from this document:

> Because of the relatively low doses to residents of contaminated territories, no evidence or likelihood of decreased fertility has been seen among males or females. Also, because the doses were so low, there was no evidence of any effect on the number of sillbirths, adverse pregnancy outcomes, delivery complications or overall health of the children.

With this statement the WHO commits a fundamental scientific sin: reversal of argument by adapting the observations to the models: 'the theoretical models cannot be wrong, but the observations are (!)'. This may remind the reader of a famous scene in the play *Leben des Galilei* by Bertolt Brecht, when the cardinals said

to Galileo Galilei: "We do not need to look, because it cannot be true."
In addition the WHO assumes the doses were low. Are these doses actually measured among the affected population, and if so, is the whole affected population screened, or only a few selected cohorts?

Reliable investigation of the effects of radioactivity in the human environment needs the registration of cases over a long time span. Independent assessment of the consequences of exposure to radioactivity is possible by means of epidemiological studies. Unfortunately such registrations usually remain undone, probably for economic reasons.
Epidemiological studies are also needed to analyze the effects of chronic exposure to low doses of a mixture of radionuclides via water and food in contaminated areas, not only after a large accident, but also in the vicinity of nominally operating nuclear power plants and reprocessing plants. A German study (KiKK 2007) and a French study (Geocap 2012) proved a significant relation between the incidence of child cancer and the living distance from a nominally operating nuclear power plant.

14 Energy on credit

Risk factor

Perhaps the biggest risk factor facing nuclear security is not a technical issue, but a paradigmatic one. The chances of nuclear terrorism and criminality and of large-scale nuclear accidents, with irreversible consequences affecting vast areas of inhabited land and millions of people, is greatly increasing as the nuclear industry persists in its current paradigm, characterized by a short time horizon, living on credit and an *après nous le déluge* attitude. The problems ensuing from the back end of the nuclear process chain cannot be handled adequately by the current commercial way of thinking. The security problems and health hazards posed by nuclear power will persist for the next century, even if the waste problem were to be tackled vigorously from this moment on, and even if the world's nuclear power stations were all closed down today.

System boundaries and time horizon

A fundamental issue in the discussion of nuclear energy is the scope of the arguments. Does one take the entire nuclear process chain into account, or only one part of it, usually the most visible part, the nuclear power plant itself? Does one use economic arguments, or physical arguments, or does one conveniently mix up economic and physical arguments without explicitly defining the scope of the arguments? What timescale is used, when discussing nuclear energy? A few years until the next election, a decade according to an authoritative scenario of the nuclear industry, or the whole cradle-to-grave period of a nuclear power station and its associated facilities viewed as one system?

Assessment of the implications of nuclear power should take the whole cradle-to-grave period into account: the timeframe that covers all industrial activities directly related to a particular power plant, from uranium mining through definitive disposal in a geologic repository of the last container of radioactive waste. The cradle-to-grave (c2g) period of a nuclear power plant will last at least a century and the existing nuclear power plants are not much further than halfway through their c2g period. During the second half of its c2g period a nuclear power station does not generate profits anymore. The greatest challenges with respect to nuclear security originate from the activities and processes occurring in the second half of the c2g period. It is precisely these processes which are shrouded by the greatest uncertainties and unknowns. So for appraisal of nuclear security now and in the future assessment of the complete c2g period is of utmost importance.

The nuclear process chain encompasses a substantial number of partial processes, which are run by different companies in widely dispersed places (sometimes on different continents) and often at widely different points in time. The time lag between processes directly related to one particular nuclear power station may vary from a few years to more than a century.
Economic calculations are done by the company, consequently comprising only one partial process of the nuclear chain at a time, and have a short time horizon, usually no more than a couple of years. This way of thinking does not result in a reliable overview of the hazards of the complete nuclear process chain.

Physical energy analysis

Arguments based on the free-market paradigm are not well suited to assess the implications of nuclear power in a global perspective with a long time horizon. Only a method based on unambiguously defined quantities, which do not depend on political and economic viewpoints, is appropriate.
Answers to questions regarding nuclear security, energy security, public health safety and climate security (CO_2 emissions) of nuclear power can be found only by means of a complete life-cycle assessment (LCA), covering the full cradle-to-grave period, and a physical energy analyis of the complete nuclear process chain. It is essential that all material and energy flows involved in applied nuclear technology are analyzed and accounted for in energy balances. Materials and constructions required in the process chain are represented in the energy balance by the amount of energy consumed by their production from raw materials as found in nature. In this way it is possible to express the material and energy inputs and outputs of a technical system in one unit of one unambiguous quantity: energy units.
These balances should include the investments of future processes that are directly coupled to the present-day operation of nuclear power plants. Energy is a conserved quantity, so unambiguous comparison of the benefits and drawbacks of different energy technologies is only possible by means of energy analyses of the involved energy systems, each spanning their full c2g period. Balances in monetary units depend on a number of variable assumptions, changing with time and location.

Energy debt

As a result of the living-on-credit paradigm prevailing in the nuclear industry, all human-made radioactivity ever generated is still stored in makeshift facilities. Isolation from the biosphere of all radioactive materials in the least risky way will require high investments of energy, materials and human resources. Adequate completion of the nuclear back end is a *conditio sine qua non* to secure our children, grandchildren and future generations against the insidious hazards of the tremendous quantities of human-made radioactivity.
Notably the following activities of the back end of the nuclear process chain will be demanding:

- dismantling and site cleanup of nuclear power plants
- dismantling and site cleanup of reprocessing plants
- durable packaging of spent fuel
- rendering the inventories of plutonium, uranium-233, neptunium and americium unusable for nuclear explosives and packaging the resulting product in durable containers for final disposal in a geologic repository
- cleanup of temporary waste storage facilities
- durable packaging of radioactive wastes other than spent fuel, including reprocessing waste and dismantling waste
- construction of the required geologic repositories
- definitive storage of all radioactive waste in geologic repositories and filling the remaining volumes of the galleries and access tunnels of the repositories with bentonite-sand.

The fulfillment of the back end processes involve large-scale industrial activities, requiring massive amounts of energy and high-grade materials; these future investments are called the *energy debt*.

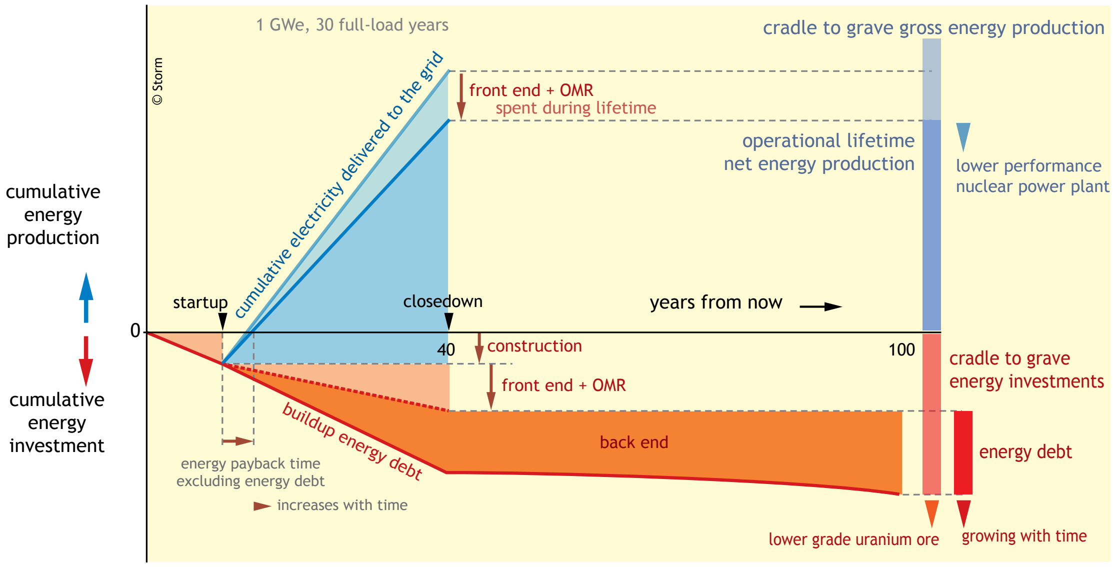

Figure 4

Dynamic energy balance of the nuclear energy system. The vertical scale has energy units, the horizontal scale is a timescale. The reactor is assumed to operate continuously at full power for 30 years (average load factor 100%). No reactor in the world ever reached this production level, the current world average is about 22 full-load years. OMR stands for operation, maintenance and refurbishments. The graph is roughly at scale. The lifetime net energy production will decrease with time, because of the increasing energy input of the front end part due to the decreasing quality of uranium ores. The energy debt increases with time due to spontaneous degrading processes (ageing).

The energy debt can be roughly estimated by a physical analysis of the processes needed to safely handle the radioactive materials generated during the operational lifetime of the nuclear power plant. The energy debt built up during construction of the nuclear power plant is repaid during the first years of the operational lifetime. Figure 4 represents a dynamic energy balance of the full nuclear process chain, from cradle to grave. For a comprehensive analysis of the energy balance of nuclear power see Storm & Smith 2008 and Storm 2012.

The size of the nuclear energy debt is unprecedented in history. Each currently operating nuclear power plant leaves behind an energy debt as large as approximately one third of its lifetime energy production. During the next decades this debt fraction will rise considerably, due to several factors:

- Increasing amount of radioactive materials generated as long as nuclear power generation is being continued, and an increasing number of temporary storage sites.
- Inevitable deterioration and ageing of materials and constructions of the temporary storage facilities of radioactive waste. The lower the quality of those facilities, the more energy and materials are required to upgrade them to a safe standard.
- Increasing efforts needed for maintenance and safeguarding of the temporary storage facilities, a consequence of the two points above.
- Increasing energy intensity of the required materials, as a result of decreasing ore grades and greater depths of the mineral deposits. For example: with time more energy has to be invested to obtain one kilogram of steel from iron ore deposits in the earth's crust.

- Increasing energy intensity in extraction of the mineral energy sources (chiefly fossil fuels): more energy is needed to recover a unit of useful energy from the earth's crust, due to the ongoing depletion of easy oil, gas and coal resources and exploitation of increasingly harder recoverable resources. This effect comes on top of the preceding effects.

15 Economic challenge

Financial debt

Obviously the energy debt will translate into a financial debt, for there is a strong connection between the cost of an activity in monetary units at one hand and the consumption of energy, materials and human effort of that activity on the other hand.
The financial debt ensuing from the energy debt and material debt has a character fundamentally different from the monetary debts economists are used to. Present economic concepts may be iincapable of handling the problems and risks posed by the nuclear heritage, in view of the following characteristics:

- Energy is a conserved quantity and for that reason the energy debt and consequently the corresponding financial debt are not discountable and cannot be written off as uncollectable. The energy debt is not subject to monetary-like depreciation, on the contrary, it will increase with time, as explained above.
- The timescale of over a 100 years (see Figure 4) is unprecedented in history.
- The massive investments of energy, materials, human resources and economic means do not contribute to the improvement of the economic infrastructure and must be considered to be pure losses. As the investments are used to isolate the radioactive wastes including their safe storage away from the human environment, the profits of the investments are apt to vanish from the economic system forever.
- Increasing energy intensity of materials will translate into a higher cost per unit product. The longer the defnitive and safe disposal of radioactive waste is postponed, the higher the cost per unit waste will have in order to achieve a given level of security.
- In addition to the unavoidable growth over time of the energy debt, measured in physical energy units, energy from fossil fuels will become more expensive with time, due to reasons explained above.

All growth effects come on top of each other and cause a steep exponential growth of the cost of maintaining our security standards. If the world economy stagnates or even declines, it will become more demanding to allocate economic activities to manage the radioactive wastes in the proper fashion. These observations point to an increasing risk of making less than optimal choices on how to isolate the radioactive legacy of nuclear power from the human environment. Consequently the security and health risks of nuclear power rise with time.

Misconception

The view that the solution of the radioactive waste problem is a matter of advanced technology is a misconception, for the immobilization of radioactivity is a Second Law problem. It is not possible by use of advanced, yet to be developed, technology to prevent the spread and dispersion of radioactivity into the environment with less effort than it would require at this moment. Spread can only be limited by dedicated human efforts, using mature conventional technology, involving massive amounts of useful energy and materials. As useful energy and materials are becoming increasingly scarce, the chances of solving the radioactive waste problem in the least dangerous way can only decline with time, and so will nuclear security.

Human resources

An additional problem may become shortages of sufficiently skilled workforces to perform these demanding tasks. If nuclear power is phased out, the required expertise to cope with the nuclear heritage may fade away quickly.
The back-end processes of the nuclear chain will take many decades after closedown of the reactor. Great numbers of highly skilled people will be needed to perform these processes. Even these days the nuclear industry has difficulty recruiting and educating enough highly skilled workers to sustain and operate its facilities and nuclear power plants.
Massive amounts of radioactive materials need to be processed after the closedown of a nuclear power plant, a part of which is highly radioactive. Even if the last nuclear power plant were shut down today, the economy has to sustain a nuclear workforce until long past the year 2100. This workforce does not contribute to any improvement of the energy supply. Its sole task is to prevent the nuclear legacy from becoming disastrous. One might wonder if enough young people would opt for the required rigorous education and training and if a free market-oriented economy could easily support such a workforce for such a long period with no return on investments.

Dismantling costs

A first indication of the financial investments to pay off the energy debt is the publication of some preliminary cost figures by the British Nuclear Decommissioning Authority (NDA), amounting to over €7bn per GWe for nuclear power plants, or 100-200% of the original construction cost (NDA 2006). Most likely the final cost will be higher.
The cost of the decommissioning and dismantling of a reprocessing plant will rise to astronomical numbers. For the reprocessing plant at Sellafield (UK) the preliminarily cost estimates vary from GBP38bn (NDA 2009) to GBP50-100bn (*Nature*, 23 November 2006 p 245) and will take some 130 years. The cost of dismantling and cleanup of the complex at La Hague in France can only be guessed at, but will almost certainly be higher because it is a larger plant than Sellafield.
Studies by the RAND Corporation (RAND 1981, RAND 1979) proved that the costs of large projects involving new technology are always underestimated at the start. The causes of the cost overruns observed by the RAND studies perfectly apply to the present nuclear projects. Cost overruns are the rule in the nuclear industry.

Compare the preliminary cost estimate of decommissioning Sellafield with the final cost of the American Apollo project, which succeeded in putting the first man on the moon in 1969 (Apollo 11) and landing five crews thereafter. The final cost of the entire Apollo project, which started essentially from scratch, were less than €100 bn in €(2009). So the decommissioning and dismantling of the Sellafield reprocessing plant, will cost the same or even more than the entire, inspiring Apollo project (1961-1975), with its huge technological spinoff.

The decommissioning and dismantling of the US West Valley reprocessing plant, which operated from 1966-1972 and reprocessed 640 tonnes of spent fuel, will cost from 2007 on at least €4bn (€(2009)) and will take another 40 years to complete. Very likely the final cost will be considerably higher. Up until 2007 several billions of dollars already have been spent on West Valley (UCS 2007). The total cost will amount to more than 40 times (!) the construction cost of the plant. If all goes according to the current plans, the decommissioning and dismantling of the US West Valley reprocessing plant would take a period of 70 years. In the meantime the radioactive pollution of the groundwater and creeks in the vicinity of the plant is still ongoing and so are the health risks to the local inhabitants.

Above figures of Sellafield and West Valley point to a specific reprocessing cost of some €10M per metric tonne of spent fuel, excluding the costs of construction and operation of the plants. How viable is reprocessing from an economic point of view?
The cost of the cleanup of a part of the military nuclear site at Hanford in the USA is estimated at some USD112bn through Fiscal Year 2090 (www.hanford.gov). These costs probably do not include the cost of dismantling and cleanup of the nuclear facilities at the site. The problems arising with the cleanup, time delays of many years and massive cost overruns, are not encouraging.

View of the nuclear industry

The World Nuclear Association (WNA), presenting itself as the representative of the nuclear industry, asserts (WNA 2012a and 2012b):

> Nuclear power is the only energy industry which takes full responsibility for all its wastes, and costs this into the product.

This WNA statement is in sharp conflict with the empirical evidence, facts and arguments presented in this report and also with the following observations:

- In the USA the federal government is responsible for the final storage of the spent fuel in a geological repository. Because of this, by definition the American taxpayer bears financial liability for the decommissioning and dismantling of the nuclear power plants.
- In the UK the closed down nuclear power plants are sold for a symbolic amount to the government, who takes on the responsibility of the cleanup, decommissioning and dismantling of the discarded radioactive facilities. In this case it's likely the British taxpayer also has to pay for the construction of a geologic repository plus the packaging and definitive storage of the nuclear waste.
- In France a different situation exists. Nuclear activities in France are managed by two state-owned companies: Areva and Electricité de France (EdF). Who pays the bill?
- In the Netherlands the State has the full financial responsibility for the management of radioactive waste (OECD-NEA 2005).

What is the situation in other countries, for example Russia, China, India, South Korea, Japan?

Questionable assumptions

Radioactive wastes from dismantling nuclear power plants and reprocessing plants are missing from the waste management options published by the nuclear industry, despite the tremendous volumes to be expected, counted in hundreds of thousands of cubic meters, the astronomical costs and the imperfectly known radioisotopic composition of the waste.
The nuclear industry sharply distinguishes spent fuel and high-level waste from other radioactive wastes, suggesting that those other wastes are not dangerous. Although the specific activities are orders of magnitude lower than of spent fuel and other high-level wastes, the volumes are many orders of magnitude larger and are spread over more storage facilities. Consequently the chances for individuals to contract a hazardous dose of lower levelradioactive material are accordingly greater, the more so because the safeguards of the 'not-to-worry-about' wastes are substantially less stringent than of spent fuel and other high-level wastes.

This distinction obviously has economic roots, for the final disposal options as envisioned by the nuclear industry for the 'not-to-worry-about' wastes - shallow burial and/or above-ground storage for 'only' four to ten centuries - are much cheaper than a deep geologic repository.

Apparently the nuclear industry bases its proposed solutions of radioactive waste management problems on questionable assumptions, among others:

- The assumption that future generations will keep the knowledge of the exact locations and properties of the stored 'not-to-worry-about' radioactive wastes generated centuries ago and will have the expertise and economic means to maintain the storage facilities and to safely handle the wastes in case of unexpected events.
- The assumption that future generations will have the political drive and sufficient economic means and skilled workforces at their disposal to perform the demanding tasks our generation could not handle.

16 Heading for future disasters

Economic impact of the Chernobyl disaster

The economic damage and losses of the Chernobyl disaster are not easily to define or assess. According to the Chernobyl Forum 2006 the total cost in Belarus over 30 years is estimated at US$235 billion (in 2005 dollars). In its report the Chernobyl Forum stated that between 5% and 7% of government spending in Ukraine still related to Chernobyl, while in Belarus over $13bn is thought to have been spent between 1991 and 2003, with 22% of national budget having been Chernobyl-related in 1991, falling to 6% by 2002. Much of the current cost is related to the payment of Chernobyl-related social benefits to some 7 million people across the three countries.
A significant economic impact at the time was the removal of 784,320 ha of agricultural land and 694,200 ha of forest from production. While much of this has been returned to use, agricultural production costs have risen due to the need for special cultivation techniques, fertilizers and additives. The costs of dismantling and cleanup of the Chernobyl site are not included in above estimates.

Economic impact of the Fukushima disaster

Obviously the socio-economic impact of the Fukushima disaster is extensive. Many tens of thousands of people have been evacuated from their homes, without any prospect of a safe return. Various effects of Fukushima are discussed by Dorfman et al. 2013.
Liabilities and compensation claims of the disaster might be measured in hundreds of billions of euros. The cleanup of the site is preliminarily estimated at some €250bn (NDreport 2011). One may wonder if these extreme costs will counterbalance the benefits of nuclear power. Fukushima might be not the last nuclear disaster of its class.

Economic burden

As a result of its *après nous le déluge* attitude the nuclear world is building up an economic challenge of unprecedented size. At some moment the reprocessing plants at Sellafield and La Hague – limiting the scope to the European situation – have to be decommissioned and dismantled. These activities might cost many 100s of billions of euros and will require massive efforts over decades, as pointed out above. The investments are increasing with time due to an increasing contamination of the buildings and constructions with all kinds of radionuclides from spent fuel. Also if the reprocessing plants closed down today, the dismantling investments would still increase over time, due to the unavoidable and progressive degrading processes of the materials and constructions and other causes mentioned above.

Even in times of a booming economy dismantling and site cleanup of a reprocessing plant would be a highly demanding task. What about the prospects in a declining economy?
In addition to the reprocessing plants, all presently operating nuclear power stations are to be

decommissioned and dismantled someday. Preliminary indications point to costs of one to two times the construction cost for each reactor.

Après nous le déluge

Any country with an appreciable number of nuclear power plants, such as France, Great Brittain and the United States, should reckon on economic efforts of Apollo project size, many hundreds of billions of euros, to keep their territory (and of the neighboring countries) habitable. Would the decision makers foster such efforts, or does the world need another Chernobyl/Fukushima disaster? That may happen in Europe or in the USA. The current way of economic thinking, pursuing only short-term profit goals, is not reassuring in this respect.

With respect to radioactive waste problems and health risks the nuclear world seems to foster a culture of downplaying and concealing risks combined with an unrealistic belief in unproved and unfeasible technical concepts. This paradigm is exacerbated by a chronic habitus of living on credit that may be best described as an *après nous le déluge* attitude, which seems to be based on questionable arguments and fallacies, such as:

> Technology advances with time and future generations will be richer than our generation, so they will have more economic means and better technological possibilities at their disposal to handle the waste problem.

Or, as John Broome put it (Broome 2008):

> How should we – all of us living today – evaluate the well-being of future generations, given that they are likely to have more material goods than we do?

A nuclear disaster cannot be prevented by denying its breeding ground.

Conclusions

Civil application of nuclear technology hides serious threats to the economic, political and societal stability of vast populations, affecting the health of millions of people. Three pathways of such disasters are:

– use of nuclear explosives by terrorists,

– terroristic attacks with conventional weapons on nuclear power plants, spent fuel cooling pools and reprocessing plants,

– severe accidents at nuclear power plants, spent fuel cooling pools and reprocessing plants.

The technology required to make a crude nuclear explosive is available in freely available literature.

Very large nuclear security problems are raised by reprocessing spent fuel. In this process bomb-usable fissile materials, plutonium, neptunium and americium, are separated from spent fuel. Without reprocessing bomb-usable fissile material can only be obtained by enrichment of uranium.

Application of plutonium in MOX fuel in light-water reactors has a negative energy balance. The use of MOX fuel raises serious security risks, due to the frequent shipments of substantial quantities of separated plutonium and of fresh MOX fuel. Both materials pose a high risk of theft and can be used by terrorists to produce crude nuclear explosives without needing advanced chemistry or equipment.

Neptunium and americium are outside international control. Only a few countries contribute to a voluntary monitoring scheme.

Thorium-based reactors produce uranium-233, which has to be separated by reprocessing in order to operate such reactors. Uranium-233 is comparable to plutonium as bomb material. The safeguards for uranium-233 are unclear.

Inherently safe nuclear power is inherently impossible. This follows from the Second Law of thermodynamics.

The choices of which nuclear security risks are allowable are set by short-term economic priorities.
Standards for allowable exposure to radioactivity are based on models. These models are flexible under economic pressure. Empirical evidence that is not compatible with the models is usually ignored.

The International Atomic Energy Agency (IAEA) plays a dominant role in the nuclear world. The IAEA is not an independent scientific institute for two reasons: the IAEA has vested interests in nuclear power and its publications have to be approved by the member states of the IAEA.

The official statements of the World Health Organization (WHO) on nuclear matters are not allowed to deviate from those of the IAEA.

The nuclear industry fosters a persistent *après nous le déluge* attitude and a culture of downplaying the risks. The world is heading for more Chernobyl-class nuclear disasters, as evidenced by events in Japan.

Deferring action on existing safety requirements and responsibilities, leaving them for the future to deal with, might actually be or create the biggest nuclear security issue of all.

In cauda venenum

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