Nuclear terrorism

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Note
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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 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.

These quotes indicate that international safeguarding system for neptunium and americium was not watertight in 2006.

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 (2015) 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 50-100 times more nuclei present in natural uranium, and consequently generate 50-100 times more energy from 1 kg uranium, than the conventional once-through system based on thermal-neutron, mostly light-water reactors (LWRs). The most advanced power reactors presently operational cannot fission more than 0.5% of the nuclei in natural uranium: uranium 235 and uranium-238 via plutonium-239.
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, realization 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 inherently 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.

5 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.
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> . . .
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> 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.

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