The Proliferation Consequences of Global Stocks of Separated Civil Plutonium

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Future decisions about the global stocks of civil plutonium, separated from spent nuclear-power reactor fuel elements in chemical reprocessing plants, is of considerable importance for nuclear-weapon proliferation. This paper will discuss the size and location of plutonium stocks, the potential use of plutonium produced in civil nuclear-power reactors to fabricate nuclear weapons and nuclear explosives, the methods of disposing of civil plutonium, and the importance of the future of civil plutonium stocks for the NPT.

Inadequate control of stocks of plutonium will frustrate efforts to prevent the spread of nuclear weapons, particularly to countries that do not now have them. It will also make it easier for terrorist groups to acquire some of the material and construct nuclear explosives of their own. Any method used for the disposal of plutonium should give a very high level of assurance that plutonium cannot be extracted illegally for use in nuclear weapons or nuclear explosives or for use outside current international non-proliferation safeguards.

Plutonium production

Almost all plutonium is produced, as an inevitable by-product, in nuclear reactors. Since 1945, the world has produced a huge amount of plutonium – a total of about 1,500 tonnes. About 250 tonnes of this plutonium were produced for use in nuclear weapons. The other 1,250 tonnes are "civil" plutonium, produced as an inevitable by-product by civilian nuclear power reactors while they are generating electricity. The amount of civil plutonium is increasing significantly. The world's nuclear power reactors (437 are operating in 32 countries) are producing an additional 70 tonnes of plutonium a year.

Nuclear-power reactors are normally fuelled with uranium. The uranium contains two isotopes, uranium-235 and uranium-238. In the reactor, nuclear fission occurs, mainly in uranium-235. Fission processes release energy, which is used to produce heat, which in turn is used to produce steam from water, which is used to turn a turbine to produce electricity.

During fission in the reactor uranium fuel, two or three neutrons are also emitted from the original uranium-235 nucleus. If one of these neutrons is captured by the nucleus of an atom of the more stable uranium-238 it will cause fission only if it is travelling at a very high speed. If it is not, as is normally the case, a nucleus of the radioactive isotope neptunium-239 will be produced that will decay into plutonium-239, another fissile isotope. Therefore, as the uranium fuel undergoes fission and is gradually used up in the reactor, an increasing amount of plutonium-239 is inevitably produced.

But plutonium-239 can also capture neutrons to become plutonium-240, which in turn can capture neutrons to become plutonium-241, and so on. Consequently, a mixture of plutonium isotopes is gradually produced in the reactor fuel. To obtain plutonium, it has first to be separated out from the unused uranium and fission products in spent uranium reactor fuel elements.

When they are removed from a nuclear-power reactor, spent fuel elements are stored at the reactor site for a few years. They can then be sent to a plant, called a reprocessing plant, which will chemically separate plutonium from the spent fuel elements. The spent reactor fuel elements contain unused uranium and fission products as well as plutonium. These three substances are chemically separated from each other by dissolving them in nitric acid with the objective of producing plutonium.

Six commercial scale reprocessing plants are currently operating in four countries: two at Sellafield, Britain; two at La Hague, France; one at Chelyabinsk, Russia; and one at Tokai Mura, Japan. A second Japanese plant, at Rokkasho Mura, is scheduled to start operating soon after the year 2006. Small plants are operating at Kalpakkam and Tarapur in India.

Global stocks of plutonium

Plutonium was first produced in significant amounts as part of the Manhattan project, set up by the United States during the Second World War to manufacture nuclear weapons. The bomb dropped on Nagasaki was a plutonium bomb.

Most military production of plutonium in the established nuclear-weapon powers (China, France, Russia, the UK, and the USA) has halted. But amounts of plutonium in commercial plutonium programmes are increasing dramatically. In France, Japan, Russia, and the UK stocks of civil plutonium will increase by as much as 125 tonnes by 2015, equal to half of all the plutonium produced by the nuclear-weapon states for use in nuclear weapons during the Cold War. Stocks of civil plutonium have now (mid-2005) reached 205 tonnes, rivalling the 250 tonnes in military stocks. In the next ten years, global stocks of civil plutonium will total about 330 tonnes (1).

Currently, twelve countries have stocks of civil plutonium. The UK has a stock of about 71 tonnes; France has a stock of about 46 tonnes; Japan has about 39 tonnes; Russia has about 37 tonnes; the USA has about 5 tonnes; Belgium has about 4 tonnes; Sweden has about 0.83 tonnes; Spain has about 0.63; Switzerland has about 0.6 tonnes; India has about 0.5 tonnes; and the Netherlands has about 0.2 tonnes. France, Russia, Japan, and the UK own about 94 per cent of the world's civil plutonium. (2)

Types of plutonium

There are various grades of plutonium, each with different isotopic compositions depending on the way in which the reactor producing it is operated. Plutonium produced in civil nuclear-power reactors operated for the most economical production of electricity is called reactor-grade plutonium. Plutonium produced in military plutonium production reactors, specifically for use in nuclear weapons, is called weapon-grade plutonium. Weapon-grade plutonium typically contains 93 per cent of plutonium-239 and about 7 per cent of plutonium-240. Reactor-grade plutonium typically contains about 60 per cent plutonium-239, about 20 per cent of plutonium-240.

Usability of reactor-grade plutonium in nuclear weapons

It is now generally recognised that nuclear weapons can be made from reactor-grade plutonium although those made using weapon-grade plutonium are somewhat more effective (3). Official recognition that reactor-grade plutonium can be used to fabricate nuclear weapons was given by, for example, Lord Gilbert in the UK (4). It is for this reason that reactor-grade plutonium is normally subjected to national and international security and safeguards measures in an effort to detect and deter its diversion or acquisition by countries or terrorist groups.

Weapon designers prefer weapon-grade to reactor-grade plutonium mainly because of the spontaneous fission that occurs in plutonium-240. If a nuclear weapon is made from reactor-grade plutonium, spontaneous fission occurring in the core of the weapon made causes it to heat up. To avoid the distortion of the core by this heat, measures must be taken to dissipate some it, although this is not a difficult problem.

Nevertheless, some official statements still imply that reactor-grade plutonium cannot be used in nuclear weapons or nuclear explosive devices. For example, Ryukichi Imai, former Japanese Ambassador for Non-Proliferation, stated that:

> *"Reactor-grade plutonium is of a nature quite different from what goes into the making of weapons . . . Whatever the details of this plutonium, it is quite unfit to make a bomb."* (5)

But, as Robert Seldon of Lawrence Livermore Laboratory explains:

> *"All plutonium can be used directly in nuclear explosives. The concept of . . . plutonium which is not suitable for explosives is fallacious. A high content of the plutonium 240 isotope (reactor-grade plutonium) is a complication, but not a preventative."* (6)

The former Director General of the International Atomic Energy Agency (IAEA), Hans Blix, stressed that the IAEA:

> *"considers high burn-up reactor-grade plutonium and in general plutonium of any isotopic composition...to be capable of use in a nuclear explosive device. There is no debate on the matter in the Agency's Department of Safeguards."* (7)

And at a conference in Vienna in June 1997, Matthew Bunn, who chaired the US National Academy of Sciences analysis of options for the disposal of plutonium removed from nuclear weapons, made a crucially important statement based on recently declassified material "of unprecedented detail on this subject":

> *"For an unsophisticated proliferator, making a crude bomb with a reliable, assured yield of a kiloton or more -- and hence a destructive radius about one-third to one-half that of the Hiroshima bomb -- from reactor-grade plutonium would require no more sophistication than making a bomb from weapon-grade plutonium. And major weapon states like the United States and Russia could, if they chose to do so, make bombs with reactor-grade plutonium with*

> *yield, weight, and reliability characteristics similar to those made from weapon-grade plutonium. That they have not chosen to do so in the past has to do with convenience and a desire to avoid radiation doses to workers and military personnel, not the difficulty of accomplishing the job. Indeed, one Russian weapon-designer who has focused on this issue in detail criticized the information declassified by the US Department of Energy for failing to point out that in some respects if would actually be easier for an unsophisticated proliferator to make a bomb from reactor-grade plutonium (as no neutron generator would be required)."* (8)

That reactor-grade plutonium can be used to fabricate nuclear weapons was proved by the British who exploded such a device in 1956 (9) and by the Americans who exploded at least one such device in the 1960s. This is why reactor-grade plutonium is also known as weapon-usable plutonium.

The critical mass of a fissile material, such as plutonium, is the minimum mass necessary to sustain a nuclear-fission chain reaction and, therefore, to produce a nuclear explosion. No explosion occurs in a mass of plutonium below the critical mass. If the mass is more than critical (i.e., it is super-critical) the fission chain reaction is sustained for as long as the mass of plutonium remains super-critical. The critical mass of a bare sphere of reactor-grade plutonium metal is about 13 kilograms, a sphere of about six centimetres in diameter. The critical mass of a bare sphere of weapon-grade plutonium metal is about 11 kilograms. (10)

If the sphere of plutonium metal is surrounded by a shell of material, such as beryllium or uranium, neutrons that escape from the sphere without producing a fission event are reflected back into the sphere. A reflector, therefore, reduces the critical mass. The reduction can be considerable. A thick reflector will reduce the critical mass by a factor of two or more. Modern nuclear weapons contain less than 4 kilograms of weapon-grade plutonium.

Reasons for and against the reprocessing of civil plutonium

Spent nuclear power reactor fuel elements do not in general have to be reprocessed. In fact, 75 or 80 per cent of the plutonium still contained in spent civilian reactor fuel elements will have to be disposed of without reprocessing the elements. Only about 20 per cent of the plutonium contained in the 180,000 tonnes of spent fuel rods discharged by civilian reactors has been separated in reprocessing plants, and, according to global plans for civil reprocessing, this percentage is unlikely to increase significantly in the foreseeable future. The remaining spent fuel elements will be stored until they can be permanently disposed of in a geological repository – such as the one planned by the USA at Yucca Mountain.

The reasons put forward for continued reprocessing are as follows:

- reprocessing is the only way of producing plutonium for nuclear weapons – this was in fact the original reason for building reprocessing plants;
- it recovers unused uranium and plutonium from spent fuel that can be reused as nuclear fuel (in the past but generally no longer, it was thought that the plutonium would be used to fuel fast breeder reactors); and

- it makes the management of radioactive waste easier by separating out radioactive materials that can be stored and eventually permanently disposed of.

The reasons against reprocessing are that:
- it results in large discharges of radioactivity into both the marine environment and the atmosphere;
- it increases the volume of radioactive waste by about 150 times;
- it results in the transportation by road, rail and sea of spent fuel from reactors that may be overseas to a reprocessing plant and the subsequent transport of high-level waste and plutonium back to the country that owns it; and
- it is the only way of producing plutonium for nuclear weapons.

The latter reason against reprocessing, coupled with the difficulty of adequately safeguarding a commercial reprocessing plant, explains why many people believe that reprocessing should be stopped.

Using existing and foreseeable safeguards technology it is not possible for the IAEA to detect in a timely manner the diversion of quantities of weapon-usable fissile materials that could be used to fabricate one or more, or even many, nuclear weapons. This has nothing to do with the competence of IAEA safeguards inspectors. It is about the limitations of safeguards technologies.

Safeguarding the plutonium in spent nuclear reactor fuel elements before reprocessing is relatively simple – it is just a matter of counting the number of the elements. The problems arise when the plutonium is removed from spent reactor fuel elements in a commercial reprocessing plant.

Commercial reprocessing plants deal typically with tonnes of plutonium per year. A good nuclear-weapons designer could construct a nuclear weapon from 3 or 4 kilograms of this reactor-grade plutonium. To ensure the timely detection of the diversion of such a small amount of plutonium in a plant where so much plutonium is handled requires very precise safeguards techniques, requiring significantly more precision than is currently available.

How can global plutonium stocks be disposed of?

Even if all reprocessing plants are closed down, the world will have to deal with large global stocks of plutonium. Plutonium leaves a reprocessing plant as plutonium dioxide. It is generally kept in a plutonium store in cans containing about one or two kilograms of plutonium dioxide. The amount in a can is strictly limited (to much less than the critical mass) to prevent the danger that it will become critical. Plutonium stores are designed in a way that prevents the cans being placed too close together.

The plutonium could be left in store until the decision about what to do with it in the long term is made. The time is, in practice, limited because the plutonium contains some of the isotope plutonium-241. The radioactive decay of plutonium-241 produced the isotope americium-241 that emits gamma radiation. After a period in storage, the radiation dose from the americium-241 would require substantial radiation shielding. Eventually, it would be necessary to chemically process the plutonium to separate the americium-241 from it. For plutonium produced in Advanced Gas Cooled Reactors and Light Water Reactors, the period is after about 10 to 15 years of storage. Plutonium from Magnox reactors could be stored for a longer period before requiring treatment the period is about 55 years. (11)

For this reason, it is generally reckoned that reactor-grade plutonium can normally be stored with adequate safety only in the medium or short term. In the longer term, the plutonium dioxide in store could be immobilised and eventually permanently disposed of in a geological repository. Or the plutonium dioxide could be mixed with uranium dioxide to make a mixed oxide (MOX) nuclear fuel that could be used in a nuclear-power reactor instead of uranium dioxide.

A percentage of stored plutonium (in the case of British plutonium it is 5 per cent) is unsuitable for use as reactor fuel, because of chemical contamination and a high level of americium-241. Although chemical treatment is possible to remove contaminants, it is likely to be uneconomic to do so.

A fourth possibility is transmutation in which plutonium is bombarded with neutrons in a reactor or with charged particles in an accelerator. This would convert the long-lived plutonium into radioisotopes with shorter half-lives which would decay away more rapidly. There are serious doubts about the technical feasibility and cost of transmutation on any significant scale.

The immobilisation of plutonium could be achieved by incorporating it into a ceramic or into borosilicate glass (Pyrex), a process called vitrification. Some authorities reject immobilisation of plutonium by vitrification because vitrified waste forms may be less suitable than ceramic forms in respect of plutonium incorporation and leaching. (11)

A radiation (radiological) barrier could be added to make theft of the immobilised material difficult. The barrier would be a radioactive material – perhaps, caesium-137 or high-level radioactive waste. The material could be intimately mixed with, or arranged externally to, the ceramic or glass. Some experts are against the use of a radiation barrier, arguing that it adds little to security that cannot be achieved by other methods and makes the process significantly more complex. (11)

There are serious arguments against the production and use of MOX for the disposal of plutonium. MOX fuel, a mixture of uranium and plutonium dioxides, typically contains between 3 to 10 per cent of plutonium by weight and the rest normally consists of either natural or depleted uranium.

- the cost of MOX fuel is much higher than that of normal uranium oxide fuel;
- reactors fuelled by MOX may be less safe to operate;
- the need to protect and secure MOX fuel elements kept at nuclear reactors will involve reactor operators in new physical security problems and extra expense;
- international safeguards designed to prevent nuclear proliferation are difficult to enforce at facilities associated with MOX; and
- the use of MOX increases the risk of nuclear-weapon proliferation by countries and, perhaps more seriously these days, by terrorist organisations.

Having obtained a quantity of MOX fuel by diversion or theft, a terrorist group would have little difficulty in making a crude atomic bomb. The necessary steps of chemically separating the plutonium dioxide from uranium dioxide, converting the dioxide into plutonium metal, and assembling the metal or plutonium dioxide together with conventional explosive to produce a nuclear explosion are not technologically demanding and do not require materials from specialist suppliers. The information required to carry out these operations is freely available in the open literature.

The arguments given in favour of the production and use of MOX are:

- the use of MOX allows plutonium to generate more energy in nuclear reactors rather than wasting this energy; and
- the use of MOX reduces the stockpiles of separated plutonium owned by some countries, stockpiles that are politically embarrassing because the plutonium could be used to fabricate nuclear weapons.

Conclusions

The increasing global stockpiles of weapon-usable plutonium increase the risk of the spread of nuclear weapons to countries and terrorists. Plutonium produced in civil nuclear-power reactors and separated in reprocessing plants can be stored, but normally only for a limited time of 10 to 15 years. In practice, it must then either be immobilised and disposed of in geological repositories or used as nuclear fuel in reactors.

The use of MOX in a nuclear-power reactor is not a satisfactory solution to the problem of excess plutonium stocks. A more rational solution would be to stop reprocessing of spent nuclear fuel rods to separate out the plutonium in the first place and to immobilise existing stocks of plutonium until they can be permanently disposed of.

Some argue that there is no such thing as the permanent (i.e., final) disposal of plutonium or any other radioactive waste because any ‘permanent’ disposal site would eventually leak and contaminate the environment. Radioisotopes of very long half-lives, like plutonium-239, are obviously of greatest concern. There is also concern about the possibility of criticality incidents if control over plutonium wastes is abandoned. For these reasons, a permanently managed store may be preferable, with the opportunity for retrieving the material in the future.

Recommendations

1) The operation of the few commercial reprocessing plants in the world should be stopped.
2) All spent civil nuclear-power reactor fuel elements should then be stored until they can be permanently disposed of in a suitable geological repository.
3) Existing plutonium in store should be immobilized, to put it into a passively safe form, and permanently disposed of in a suitable geological repository.
4) The production and use of MOX nuclear fuel should be halted.
5) Nations should evolve national policies about the disposal of plutonium as part of their efforts to prevent the spread of nuclear weapons to countries that do not now have them and to terrorist groups.

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