Plutonium: the international scene[*]

T. B. Cochran, PhD

Natural Resources Defense Council, Inc., 1350 New York Avenue, NW, Suite 300, Washington, D.C. 20005, USA

Since the pace at which a country's acquisition of nuclear weapons depends upon the availability of weapon-usable fissile materials, it is not enough to eliminate existing weapons: we must also have a rational policy governing the issue of plutonium, both military and civil. The ultimate objective must be the complete abolition of nuclear weapons.

Introduction

Trinity, the first nuclear device, tested at Alamogordo, New Mexico on July 16, 1945, had a plutonium core of 6.2 kg, a sizable fraction of the entire world inventory of separated plutonium. Over the next 50 years the United States government produced and separated about 103 t of plutonium. The current US inventory is about 98 t. Of this amount about 84 t is weapon-grade plutonium that was produced for weapons. With this plutonium and a much larger stock of highly enriched uranium (HEU), the United States has constructed over this 50-year period some 70,000 nuclear weapons, with the plutonium and HEU being used several times in different generations of weapons. The US operational nuclear weapon stockpile peaked in 1967 at about 32,500 warheads and is about 10,000 warheads today; the US currently plans to retain some 7,400 warheads after START II. Of the weapon-grade plutonium, about 64 t is in 21,500 plutonium pits, including those in weapons and those stored at Pantex.[1] Each pit contains, on average, 3 kg of plutonium.

Soviet/Russian warhead plutonium production, which began in 1948, probably amounts to some 150–170 t,[2,3] of which an estimated 115–130 t was actually fabricated into weapon components (the rest is assumed to be in production scrap, solutions, and residues).[†] The total (active plus reserve) Russian nuclear weapon stockpile apparently peaked in 1985 at about 45,000 warheads,[4] but some of these weapons may have had HEU cores, or composite Pu-HEU cores rather than pure plutonium pits. Thus, even if it is conservatively assumed that 10,000 of these (primarily older) weapons used exclusively HEU cores, the average plutonium content of the remaining 35,000 Russian weapons still does not exceed 4 kg.[4‡] This estimate is consistent with external gamma and neutron measurements made in 1979 of a Soviet naval cruise missile warhead in its launch tube, which indicated a plutonium mass of 3–6 kg.[5] The Russian arsenal is probably at about 25,000 warheads today, and Russia will surely retain a START II inventory comparable to that of the United States.

With the much smaller contributions from the other nuclear powers, totalling about 12 t, the global stocks of military plutonium today total about 245–265 t, or about 40,000 times the amount in the *Trinity* device.[6]

The amount of plutonium in civil reactor programme is not precisely known. A typical 1000 MWe light-water reactor produces about 200 kg of reactor-grade plutonium per year. There are about 432 operating nuclear power plants in the world with a combined capacity of about 340 000 MWe. The nuclear spent fuel discharged annually from these plants contains some 60–70 t of reactor-grade plutonium. Most of this spent fuel has not been processed, and the cumulative amount of unseparated plutonium today is in the order of 1000 t. A few countries, most notably the UK, France, Japan and Russia, have active programmes of commercial spent fuel processing. BNFL's new thermal oxide reprocessing plant (THORP) has a design capacity of 1200 t heavy metal per year (tHM/y). Operating at a nominal 60% capacity factor, THORP is capable of separating about 6–7 t of reactor-grade plutonium per year. On a global scale the ability to separate plutonium has greatly exceeded the ability to turn the plutonium into fresh reactor fuel. As a consequence the global surplus of plutonium separated from civil fuel exceeds 150 t and should exceed that separated for weapons by the year 2000. At the end of March 1994 the British Government announced that the inventory of civil plutonium in Britain amounted to 40 t.[7]

---

[*] This paper was first presented at the Royal Society, Pugwash Conferences on Science and World Affairs, Public Discussion Meeting, *Plutonium management and control*, London, 8 December 1995.

[†] The fraction of pipeline materials, i.e. solutions, scrap, and residues, in the Russian weapon programme is assumed to be comparable to that in the US weapon programme.

[‡] The apparent preference for 3–4 kilograms of plutonium per weapon, rather than some lower number, can be explained by the fact that this amount of material affords the optimal yield-to-weight ratio for the warhead.

How far to go and what steps to take?

South Africa is the only weapon state that has dismantled its nuclear arsenal – a total of six atomic bombs. The British Pugwash Group has presented the case for the United Kingdom to relinquish its nuclear weapons arsenal of about 250 nuclear weapons.[8] There are many British policymakers who may agree to deeper reduction in the nuclear arsenals but who are not prepared to see their country relinquish its status as a nuclear weapon state. Even they should be prepared to undertake now any number of beneficial steps on the road to disarmament, such as placing all or most of Britain’s SLBM warheads in inactive land-based storage. At the very least all should agree that every nation should take whatever steps are necessary now to insure that the road to abolition of nuclear weapons will not be blocked in the future. Today, at a minimum, Britain should adopt or support the steps identified in Table 1:

(a) Further deep reductions in the deployed arsenals of all nuclear-weapon states, declared and undeclared

Neither the US Senate, nor the Russian Duma, have ratified START II. Instead of negotiating further reductions, Pentagon plans, as set forth in the Nuclear Posture Review, call for retention of a hedge arsenal of some 2500 strategic warheads and almost 1000 non-strategic warheads in addition to the 3500 strategic warheads, the number allowed under START II. Russia has been silent with regard to the number of warheads it plans to retain. The UK should play a more forceful role in encouraging the US and Russia to implement START II and initiate further reductions. At a minimum, the UK should remove all nuclear warheads from alert status and place them in storage.

(b) Declarations, data exchanges, and cooperative verification measures to confirm the progressive elimination of both operational and reserve nuclear weapon stockpiles, including the permanent disassembly of nuclear warheads and bombs, the destruction of non-fissile components, and the status of fissile material components withdrawn from weapons

Last December the US government finally agreed to initiate an exchange of nuclear weapon and fissile material inventory data with the Russians. This effort has been stalled for the past ten months due to Russia’s failure to conclude an Agreement for Cooperation with the United States that is legally required before the data can be swapped. Both sides could have simply declassified the data and made it public, but Russia still fears such gestures to democracy. The UK, which has been silent about the size of its arsenal and fissile material inventories, should make a public declaration regarding its nuclear weapon and fissile material inventories and encourage the other nuclear weapon states to follow suit.

(c) Secure storage of all plutonium and HEU components withdrawn from weapons under bilateral or five-power verification pending implementation of arrangements for conversion/dilution to reactor fuel or direct disposal as vitrified waste

The US has chosen the ‘spent fuel standard’ as the criterion for the safe disposition of its excess plutonium, meaning that plutonium from weapons should be made as difficult to retrieve as the plutonium currently stored as spent civil reactor fuel. To meet this standard the United States may fabricate some of the excess plutonium into mixed-oxide (MOX) fuel and burn it in reactors on a once-through basis. The remainder of the excess plutonium likely will be mixed with fission product waste and vitrified. Russia’s Ministry of Atomic Energy (MINATOM) would like to use its excess plutonium to fuel new breeder reactors, but does not possess the financial means to implement this proposal. Meanwhile, Russian weapon-usable fissile materials are stored under inadequate physical security and material control and accounting. The British are playing a counterproductive role. While the United States is trying to convert plutonium into spent fuel, the UK is busily removing plutonium from spent fuel much faster than the separated plutonium can be burned as MOX fuel.

(d) Application in the weapon states of International Atomic Energy Agency (IAEA) or comparable multilateral safeguards to all fissile material inventories not stored in weapon-component form, and to all facilities with the capacity to use, produce, separate, enrich, or otherwise process fissile material

The nuclear-weapon states, including the UK, have refused to research, develop, and demonstrate (RD&D), much less implement, a safeguards programme for the weapon states; and the US and Russia have not initiated such an RD&D effort even on a bilateral basis.

Table 1. Steps to preserve the option of a nuclear-free world

Step 1	Further deep reductions in the deployed arsenals of all nuclear-weapon states, declared and undeclared.
Step 2	Comprehensive declarations, data exchanges, and cooperative verification measures to confirm the progressive elimination of nuclear weapons and the status of removed fissile materials.
Step 3	Secure verified interim storage of all plutonium and HEU components withdrawn from weapons.
Step 4	Application of multilateral safeguards to all fissile material inventories not stored in weapon-component form, and to all facilities with the capacity to use, produce, separate, enrich, or otherwise process fissile material.
Step 5	A global, verified cut-off in the production of fissile materials for weapon purposes.
Step 6	Capping and drawing down the world inventories of weapon-usable fissile materials, including a moratorium on programmes for the civil production and use of separated plutonium and HEU.

(e) A global, verified cut-off in the production of fissile materials for weapons purposes

Negotiations for a fissile material cut-off in the CD are going nowhere, primarily due to opposition (Pakistan) or non-participation (Israel) by the threshold states.

(f) Capping and drawing down the world inventories of weapon-usable fissile materials, including a moratorium on programmes for the civil production and use of separated plutonium and HEU

The UK, France, Japan, and Russia all continue to separate weapon-usable plutonium faster than it can be absorbed in the commercial fuel market. It is perhaps here that the UK could play the most effective role.

The appropriate role for the UK to play with respect to this last step is at least as controversial as the issue of whether the UK should retain its status as a nuclear-weapon state. Whether the aim is the abolition of all nuclear weapons, or only the protection of that option for the future, the UK should defer further chemical separation of plutonium. The use of plutonium as a civil reactor fuel should be restricted to the burning of existing stocks of plutonium from weapons and from existing separated stocks.

Why should the British defer further commercial separation of plutonium? Before addressing this issue, it may be useful first to clarify two technical issues that have clouded the debate over this issue.

How much plutonium is needed to make a nuclear weapon?

The IAEA is the UN agency responsible for ensuring the 'timely detection' of the loss or diversion of the nuclear materials needed to make a bomb from facilities in non-nuclear weapon states. Based upon advice given by nuclear-weapon states in 1967, the Agency assumed that 8 kg was the 'threshold amount' of plutonium needed for a first nuclear weapon, including losses incurred during fabrication of the device. This so-called 'significantly quantity' (SQ) limit is still the Agency's threshold limit in use today.

An SQ of 8 kg for plutonium is consistent with assuming a 30% loss in fabrication of a nuclear weapon similar to the *Trinity* device or the Nagasaki weapon, each of which had a 6.2 kg plutonium core. As indicated by Fig. 1, this IAEA criterion is technically indefensible. Even using vintage 1945 technology, 8 kg is absurdly large. Had the 6.2 kg plutonium core of the Nagasaki weapon been replaced with a 3 kg plutonium core, the yield of this weapon still would have exceeded 1 kt with no other changes in the design. During the Ranger series of tests in 1951, the US used an even smaller quantity of plutonium to achieve a 1 kt yield – utilizing the Mark 4 bomb design, which incorporated the principle of levitation (now declassified) which was first tested by the United States in the 1948 Sandstone series of tests.

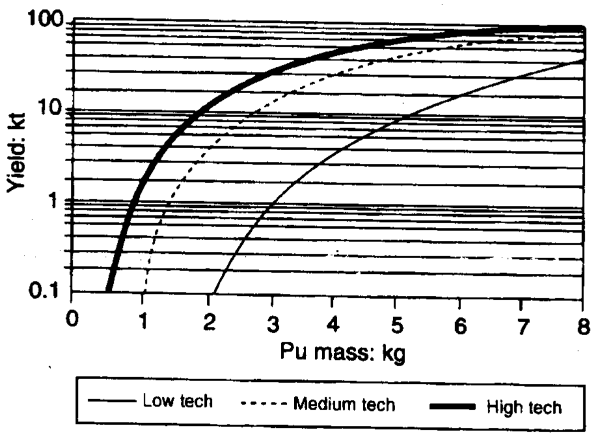

Fig. 1. Yield against Pu mass (as a function of technical capability)

The UK has now revealed that it used a 2 kg plutonium core to obtain a yield of 3 kt in its eighth test, conducted on October 11, 1956. As can be deduced from Fig. 1, the boosted primaries of some modern US warheads apparently use as little as 2 kg of plutonium compressed by only a few tens of kg of HEU. And lastly, the Russians announced that the warhead left at the Semipalatinsk test site and destroyed on May 31, 1995 contained about 1 kg of plutonium and had a design yield of 0.3 kt. Nuclear weapons with yields exceeding 1 kt can be made with as little as 1 kg of weapon-grade plutonium. The primaries of several thermonuclear warheads in the US nuclear arsenal are believed to contain no more than about 2 kg of weapon-grade plutonium.

Can efficient nuclear weapons be constructed with reactor-grade plutonium?

The curves in Fig. 1 apply to weapon-grade plutonium where the Pu-240 content is less than 7%. Most of the plutonium in the civil sector is reactor-grade with a Pu-240 content in the range of 20–35%.

Plutonium with a high Pu-240 content is less desirable for weapons purposes than weapon-grade plutonium for four reasons:

(*a*) it has a larger critical mass

(*b*) it presents a greater radiation hazard to workers and weaponeers

(*c*) it give off more thermal energy (heat) as a consequence of radioactive decay of the shorter-lived plutonium isotopes

(*d*) it has a greater rate of spontaneous fissions due to the higher concentration of Pu-240.

Regardless of its Pu-240 content, the critical mass of reactor-grade plutonium falls between that of weapon-grade plutonium and HEU. From the standpoint of critical mass, reactor-grade plutonium is preferred over HEU, a quite respectable weapon-usable material. The added radiation and thermal effects can be alleviated through shielding and design modifications.

Some advocates of civil plutonium use have argued erroneously that the higher rate of spontaneous fissions effectively 'denatures' the explosive characteristics of reactor-grade plutonium. For low technology weapon designs, the neutrons generated by the high rate of spontaneous fission of Pu-240 can increase the statistical uncertainty of the yield by 'preinitiating' the chain reaction before the desired compression of the plutonium core has been achieved. In spite of this difficulty, *militarily useful weapons with predictable yields in the kiloton range can be constructed based on low technology designs with reactor-grade plutonium.* According to the conclusions of a recent study by the National Academy of Sciences in the United States, based in part on a classified 1994 study by scientists at the Lawrence Livermore National Laboratory:

> 'even if pre-initiation occurs at the worst possible moment (when the material first becomes compressed enough to sustain a chain reaction), the explosive yield of even a relatively simple device similar to the Nagasaki bomb would be on the order of one or a few kilotons. *While this yield is referred to as the "fizzle yield", a one kiloton bomb would still have a destruction radius roughly one third that of the Hiroshima weapon, making it a potentially fearsome explosive. Regardless of how high the concentration of troublesome isotopes is, the yield would not be less.* With a more sophisticated design, weapons could be built with reactor-grade plutonium that would be assured of having higher yields.[9]

By making use of various combinations of advanced technologies, including improved implosion techniques, the use of beryllium as a neutron reflector, boosting with deuterium and tritium, and two-stage weapon designs, it is possible to offset the problems created by the high rate of spontaneous fission of Pu-240. US Nuclear Regulatory Commissioner, Victor Gilinsky, best summed up the issue in 1976, when he stated:

> 'Of course, when reactor-grade plutonium is used there may be a penalty in performance that is considerable **or insignificant**, depending on the weapon design. But whatever we once might have thought, we now know that even simple designs, albeit with some uncertainty in yield, can serve as effective, highly powerful weapons – reliably in the kiloton range.[10]

Assuming an advanced design were attempted using reactor-grade (24% Pu-240) plutonium, the *nominal yield potential* of a modern 2–3 kg weapon-grade plutonium core could be maintained by increasing the mass of the plutonium core by about 25% – the ratio of the respective reflected critical masses. Thus, the reactor-grade equivalent of a modern 2–3 kt weapon-grade plutonium core is about 2.5–3.75 kg.

There are two additional points that are often overlooked. First, in civil spent fuel stocks, in which most of the fuel is high burnup, there is usually some low burnup fuel from which significant quantities of weapon-grade plutonium can be extracted if the low burnup fuel is processed separately. Second, it is possible that advanced isotopic separation techniques, such as advanced laser isotope separation (AVLIS), may also be available to any country with the nuclear technology and capital sufficient to support construction of breeders and reprocessing plants. The availability of such technology would erase whatever operational and technical deficiencies attend the use of reactor-grade plutonium in weapons, by allowing inventories of already separated reactor-grade material to be 'cleaned up' to weapons-grade. Indeed the US was on the verge of constructing a large plant of this type in 1989 to clean up Department of Energy stocks of fuel-grade plutonium when the Berlin Wall came down. Both France and the US are continuing to develop production-scale AVLIS technology for commercial uranium enrichment, and Israel is known to have built a small pilot-scale facility in connection with its secret nuclear weapons programme.

Why defer further commercial spent fuel reprocessing?

The above technical issues having been discussed, it remains to consider the reasons for UK deferment of further chemical separation of plutonium, as set out below (and see Table 2).

(a) Minimizing the risk of a global nuclear catastrophe

As already indicated, only an extremely small quantity of plutonium – in the order of 1–3 kg – is needed to make a nuclear weapon with a yield of at least 1 kt; and plutonium of virtually any isotopic composition can be used to make a nuclear explosive, with the penalty in terms of yield-to-weight or yield-to-volume dependent on the sophistication of the design.

Each tonne of reactor-grade plutonium stocks in the civil reactor programme represents the equivalent of 130 Nagasaki-type plutonium cores, or 270–400 modern nuclear weapon cores.

Limit the military potential of civil nuclear programmes

The current policies of the UK, France, Japan and Russia of sanctioning civil spent fuel reprocessing has resulted in a world confronted with large flows of recovered plutonium and plutonium stockpiles, a significant fraction in non-nuclear weapon states. BNFL, for example, recovers 6–7 t of reactor-grade plutonium per year at THORP by processing some 700 tHM spent fuel annually. This represents roughly 800–900 Nagasaki-type plutonium cores or 1600–2800 modern plutonium cores annually. Japan currently has plans to build a similar size reprocessing plant at Rokkasho.

Deployment of plutonium fast breeders would entail staggering amounts of nuclear weapons-usable pluto-

Table 2. Reasons for deferring further separation of plutonium in the civil nuclear fuel cycle

Reason 1	*Minimize global risk of a nuclear catastrophe* Small quantities of weapon-, fuel-, or reactor-grade plutonium can be used to make efficient, powerful nuclear bombs as well as inefficient crude bombs and terrorist explosive devices.
Reason 2	*Limit the military potential of civil nuclear programmes* 'Civil' plutonium programmes provide a legitimate civilian cover for any country to acquire and stockpile nuclear explosive materials, while they sustain a global technology base in chemical separation, processing, and metallurgy that has been (and will continue to be) applied to clandestine military programmes.
Reason 3	*Reduce global potential for NPT 'breakout'* Nations that have 'legally' acquired a stockpile of separated plutonium, or separation facilities, under safeguards, but then undergo political upheaval or a change in national strategy, could suddenly emerge as nations capable of building nuclear arsenals.
Reason 4	*Remove a barrier to destruction of weapon stocks* National stockpiles of separated 'civil' plutonium and operable Pu-production facilities will act as a barrier to deeper reductions and eventual elimination of nuclear weapons held by declared and undeclared nuclear weapon states.
Reason 5	*Adequate safeguards are not possible* National separation, recycling and breeding of plutonium on a commercial scale place an impossible burden on the current and prospective capabilities of the IAEA safeguards system to detect promptly thefts or diversions of Pu-bomb quantities from peaceful use.
Reason 6	*Ensure efficient allocation of scarce capital resources for energy development* Separation and use of plutonium in the civil nuclear fuel cycle is not justified by current or foreseeable energy market conditions, which for the next several decades at least favour investments in conservation, efficiency, and a range of competing power sources, including safer, more reliable and efficient reactor technologies not requiring the use of separated plutonium.

nium in the reactors and the supporting fuel cycle. The plutonium inventory in a single 800–1000 MWe breeder is 4–5 t. Although the net amount of plutonium produced annually in a fast breeder reactor is generally less than that produced in a conventional thermal power reactor of the same size, one-third to one-half of the fast breeder reactor fuel must be removed annually for reprocessing, plutonium recovery, and remanufacture into fresh fuel. Since the fuel will be outside the reactor for 3.5–7 years, the plutonium inventory needed to support a single commercial-size plutonium breeder is 10–20 t. If only 10 gigawatts of nations' electrical capacity were supplied by breeders – hardly enough to justify the research and development (R&D) effort in any country even if the economics were otherwise favourable – the plutonium inventory in the reactors and their supporting fuel cycle would be in the order of 100–200 t, comparable to the weapon plutonium arsenals of the United States and Russia.

Moreover, those nations (or agencies within nations) having access to the breeder fuel cycle *would not be limited to reactor-grade-Pu weapons*. About one-half of the new plutonium created in a breeder reactor – that which is bred in the blanket rods – is 'supergrade' plutonium (< 3% Pu-240), with a Pu-240 content lower than that used in US and Russian weapons. *Thus, any non-weapons country that has stocks of breeder fuel has the capacity to produce a ready stock of low-burnup plutonium that is optimally suited for weapons*; it only has to segregate and reprocess the blanket assemblies separately from the core assemblies. To maximize output of weapon-grade material, a country could blend the super-grade plutonium from the breeder blanket with existing inventories of 'fuel-grade' (> 19% Pu-240) plutonium to create a larger quantity of 'weapon-grade' (< 7% Pu-240) material.

It is noteworthy that Japan, between 1987 and 1993, acquired advanced 'centrifugal contactor' technology for separating *low-burnup* plutonium from the US Department of Energy for installation in PNC's recycle equipment and test facility (RETF) at Tokai – technology that was originally developed and tested at two US nuclear weapons production facilities: the Savannah River Plant and the Oak Ridge National Laboratory.

As will be discussed below, there is at present no technically credible means of safeguarding this material to prevent strategically significant quantities from being diverted for use in nuclear weapons. If development of plutonium breeders continues in the few remaining countries that have strong breeder R&D programmes, this will continue to legitimize breeder programmes and plutonium stockpiles in non-nuclear-weapon states that may use these programmes to cover the development of a weapons option. *India, for example, recovered the plutonium for its first nuclear device in a reprocessing plant that was ostensibly developed as part of its national breeder programme.*

Consequently, remaining breeder R&D programmes, if not deferred altogether, should be limited to conceptual design efforts only, with an emphasis on advanced proliferation-resistant fuel cycles that do not require mastery of the technology for isolating weapons-usable nuclear materials. To the extent that this goal is politically unattainable, sufficient plutonium has already been separated to meet the needs of R&D programmes, so at a minimum there is no requirement to continue separating plutonium for this purpose. In this connection it should be noted that if plutonium breeders some day prove to be economically competitive, and if the breeder fuel cycle can be safeguarded with high confidence under stringent international controls, then commercial deployment could begin with cores of non-weapons-usable 20% enriched uranium. *In other words, there is no need to accumulate a stockpile of separated plutonium today to ensure the possibility of deploying breeders at some point in the future.*

(c) Reduce the global potential for NPT 'breakout'

Reprocessing of spent fuel and the recycling of plutonium* into fresh fuel for reactors permit non-nuclear weapons states to justify the acquisition and stockpiling of nuclear weapons-usable material – ostensibly for peaceful purposes. While violating their implicit (NPT) obligation not to engage in 'preparations' for 'manufacture' of nuclear weapons, *but without violating any international safeguards agreements*, these countries could also secretly design, fabricate, or purchase non-nuclear-weapon components. By moving to a point of being within hours of having nuclear weapons (perhaps needing only to introduce the fissile material into the weapons) a nascent weapons state would have all of its options open. Under these conditions, international safeguards agreements can actually serve as a cover by concealing the signs of critical change until it is too late for diplomacy to reverse a decision to 'go nuclear'. In the 1970s a number of countries, including Pakistan, Argentina, Brazil, South Korea, and Taiwan, sought access to reprocessing technology ostensibly for peaceful purposes. *The record shows that each one of these countries also had a secret nuclear weapon development programme*. Most recently Iraq diverted HEU from its 'peaceful' research reactors with the intent of turning it into weapons.

A non-nuclear-weapon state always has the option to shift a 'peaceful' nuclear programme, based on the once-through, or open, fuel cycle to a weapons programme, but this would require the politically difficult decision to violate 'full-scope' IAEA safeguards by secretly establishing unsafeguarded fuel cycle facilities. Without civil reprocessing facilities and breeder reactors, countries wishing to develop nuclear weapons capacity face very considerable political obstacles and costs. Obtaining significant quantities of fissionable material for weapons would require that they build one or more specialized production reactors and chemical separation facilities outside of safeguards, using indigenous or black market technology.* On the other hand, acceptance of the closed fuel cycle and the plutonium breeder as a reasonable long-term energy option provides the justification for the early development of a reprocessing capability by any country. This was the route taken by India. By establishing a nuclear weapons option through a 'peaceful' plutonium-using nuclear electric generation programme, current and future proliferators can obtain quick access to massive quantities of separated weapon-usable plutonium.

A 'peaceful' plutonium recycle or fast breeder reactor programme also justifies the acquisition of a whole panoply of specialized research facilities, training, and data applicable to nuclear weapons design that would otherwise not be easily acquired, such as:

(i) fast critical assemblies, including significant quantities of weapon-grade material with which to perform reactor safety and criticality experiments in the laboratory with minimal health risk to personnel
(ii) nuclear diagnostic instrumentation and recording equipment
(iii) elaborate Monte Carlo neutronic codes, and data on material properties at high temperatures and pressures, needed for controlling the same fast-neutron spectrum used in nuclear weapons
(iv) data on plutonium metallurgy and alloys for producing plutonium fuel elements and evaluating their performance

and so on. In short, a peaceful plutonium fuel cycle programme represents an enormous head start on a nuclear weapons programme. Indeed, it represents a 'legal' path to nuclear weapons potential under the NPT.

(d) Remove a barrier to the destruction of weapon stocks

Stockpiles of separated 'civil' plutonium will act as a barrier to very deep reductions and eventual elimination of nuclear weapons held by declared and undeclared weapon states. The reality of this obstacle is immediately apparent when it is considered, for example, how far China is likely to go toward eliminating its nuclear arsenal if Japan accumulates a huge inventory of nuclear explosive materials in pursuit of a civil plutonium programme that has no plausible commercial justification for at least the next 50 years.

Likewise, how deep will be the cuts in the US nuclear weapons stockpile if Russia proceeds to large-scale deployment of the breeder fuel cycle, with its inventories of hundreds of tonnes of separated plutonium and inherent capacity for creating 'super-grade' blanket material; or if Russia merely continues to accumulate inventories of separated plutonium from operating 'civil' reprocessing plants while US military reprocessing plants are shut down? The most probable answer is that a significant fraction of the 5000 'active' and 2500 'reserve' US weapons, and 7800 stored plutonium pits, now planned for the year 2003, will stay right where they are.

---

*Or any other weapons material, such as highly enriched uranium or uranium-233.

*They could also seek international acceptance for the acquisition of a safeguarded uranium enrichment plant to produce either HEU, or excess stocks of unirradiated low enriched uranium that could be rapidly enriched to weapon-grade coincident with withdrawal from the NPT. There is now virtually zero international legitimacy for the uranium enrichment route – the only recent exception being Russia's 'agreement in principle to negotiate' the sale of a centrifuge plant under safeguards to Iran.

Professor Rotblat's dream of a nuclear weapon free world will not be realized if the UK, France, Russia and Japan continue to pursue a civil plutonium economy.

(e) On a global basis, large bulk handling facilities – reprocessing plants and plutonium fuel fabrication plants – cannot be adequately safeguarded to prevent the spread of nuclear explosive material

Adequate physical security measures are essential to prevent the theft of fissionable material, and under the present international safeguards system these are entrusted to the individual nation state, which in turn may delegate the task to private commercial entities licensed for the purpose.

Frequent and accurate material control and accounting (MC&A) measures are essential to provide a timely determination of whether any significant theft or other loss of material has occurred. This determination should in theory afford the international community the opportunity to undertake actions aimed at preventing any diverted, stolen, or otherwise missing material from being used for destructive or coercive purposes, or from posing an unrecognized threat to the environment and human health. Maintaining adequate MC&A measures is the joint responsibility of an individual nation state and international organizations – the IAEA and EURATOM.

Given the technical difficulty and cost of making the repeated measurements that are often necessary to provide a high degree of assurance that all material remains accounted for, MC&A measures are supplemented by 'containment and surveillance' (C&S) techniques (mainly seals and cameras) that are intended to maintain the integrity of measured quantities or storage areas between inspections. C&S techniques are also used to monitor access to areas where direct measurements cannot be taken, or where the error in making remote measurements is large.

It is without dispute that on a global basis physical security has not been adequate to prevent the theft of kilogram quantities of weapon-usable fissile material from civil nuclear facilities. Over the past several years, at least seven serious cases of diversion of weapon-usable fissile material have occurred. Although North Korea signed the NPT in 1985, it did not permit the IAEA to conduct inspections, as required by the Treaty, until May 1992. In the interim, US intelligence believes North Korea has extracted 8–12 kg of plutonium at the Yongbyon reprocessing plant (and possibly at one or more hot cells) using irradiated fuel rods from its 5 MWe reactor. Iraq initiated a crash programme in August 1990 to build a nuclear weapon within eight months, by recovering HEU from its inventory of French- and Russian-supplied research reactor fuel that was under IAEA safeguards. Iraq proceeded to divert the IAEA safeguarded fuel and cut the top off one of the fuel assemblies before the programme was interrupted by the Gulf War.

Three additional cases involved the theft of 1.5–3 kg of HEU, and two others involved over 100 grams of HEU or plutonium. Most, if not all, of the five cases involved materials stolen from Russian nuclear facilities, and in two cases the materials were intercepted outside Russia.

Some may attempt to dismiss these cases and cite the historical record in 'good' countries with state-of-the-art capabilities. But even here it is well established (from experience at existing civil and military chemical separation (reprocessing) plants, naval fuel facilities, and mixed-oxide fuel facilities) that it is extremely difficult (or even impossible) to provide *in practice* a sufficient level of physical security and material accounting and control at bulk handling facilities that process large amounts of nuclear weapons-usable material. The inventory differences at the THORP plant are kept secret, but on a plantwide basis are probably in the range of 0.3–1% of the throughput. On an annual basis, this represents an uncertainty in the range of 20–70 kg of plutonium.

One of the difficulties in providing adequate physical security is that theft of materials can involve a collusion of individuals, including the head of the guard force, or even the head of the company or agency. Despite having guards at every bank, employees at the Bank of Credit and Commerce, Inc. (BCCI) were able to steal millions of dollars from bank customers because the thieves were running the bank – the collusion was at the top. If the threat includes the potential for collusion involving the guard force and facility directors, providing adequate physical security in the West would require turning the facility into a heavily armed site occupied by an independent military force. In the former USSR, and now Russia, the security of fissile materials has relied heavily on guarding not only the facilities, but also the secret towns and cities where the nuclear workforce resides. These large 'closed' areas are anathema to a democratic society.

Of course, the principal role of physical security is completely reversed when the collusion involves elements of the government itself. In this case the primary mission of the security apparatus is to *hide* the programme from outside scrutiny. It is now known that at various times in the past, the governments of the United States, Japan (during World War II), former Soviet Union, United Kingdom, France, China, Israel, India, South Africa, Sweden, Argentina, Brazil, Taiwan, Pakistan, North Korea, South Korea, and Iraq have had *secret* nuclear weapons development programmes. *In light of this history, combatting the 'norm of secrecy' surrounding the operations of nuclear research and development complexes can be seen as an integral part of any serious nuclear non-proliferation strategy.* Overcoming the historic inability of the international community to penetrate beyond a nation's declared nuclear facilities to inspect undeclared sites is now understood by many countries to be a vital component of any serious effort to detect and thereby deter clandestine nuclear weapon development programmes.

The international community's principal tool for penetrating the secrecy of nuclear facilities is the power of the IAEA to conduct inspections and require adherence to strict MC&A procedures. The irony today, however, is that a 'peaceful-use' plutonium programme can be abused to aid a proliferator's requirement for *secret* fuel cycle facilities, which are becoming increasingly difficult to deploy in any case in the face of continuing improvements in remote surveillance techniques, and increasing demands for more intrusive on-site inspections. Under the prevailing interpretation of the NPT, a non-weapon state party is not barred from maintaining an implicit nuclear weapons *option*, if this is done by legally acquiring and operating sensitive facilities under safeguards 'for peaceful purposes'. In other words, the IAEA could well improve its capabilities for uncovering, and thereby preventing, operation of clandestine nuclear facilities, only to find that this non-proliferation strategy has been invalidated by a legal proliferation of *declared* fuel cycle facilities.

While there are numerous shortcomings in the design and implementation of IAEA safeguards, the focus here will be the implications of three technical flaws.

(i) As noted previously, the IAEA's SQ values are technically incorrect: they are far too high.
(ii) Detection of the diversion of an SQ amount applies to an individual material balance area, instead of the entire facility, or even country.
(iii) The IAEA's timely detection criterion cannot be met.

The IAEA permits facilities to reduce inventory uncertainties by subdividing the facility into numerous material balance areas. The facilities in fact should be so subdivided; this provides added protection against a single insider threat. But it must be recognized that this does not afford adequate protection against a collusion of individuals, particularly in scenarios where elements of the state apparatus itself are engaged in the diversion.

Detection time (the maximum time that should elapse between diversion and detection of a significant quantity) should be in the same range as the conversion time, defined as the time required to convert different forms of nuclear material into components of nuclear weapons. For metallic plutonium and HEU, the conversion time is seven to ten days; for other compounds of these materials, one to three weeks. These times are already much shorter than the period between inventories at any fuel reprocessing plant operating today. Thus, there can be no assurance that the primary objective of safeguards – the timely detection of the loss or diversion of significant quantities of plutonium – is now being, or can be, met.

To meet the timely detection criteria, reprocessing plants would have to undergo clean-out inventories every few days, or weeks. But this would reduce their annual throughput – and utility – practically to zero. It would also drive up the cost of reprocessing. Plutonium recycle (the use of MOX fuel in standard commercial light-water reactors (LWRs) is already uneconomical due to the high costs of reprocessing and fuel fabrication even when conducted without a technically adequate level of safeguards. Similarly, the cost of the fast breeder fuel cycle is already vastly greater than that of the LWR operating on the once-through cycle without plutonium recycle. Ensuring adequate safeguards on the breeder fuel cycle would only widen this cost disparity.

In Western Europe and Japan, consideration is being given to near-real-time accountancy (NRTA) as a means of improving the sensitivity and timeliness of detection. NRTA involves taking inventories at frequent intervals, typically once a week, without shutting down the facility. Effective implementation of NRTA and similar concepts may well be opposed by plant operators due to the added costs that would be imposed. In any case, the methods and adequacy of practical NRTA system implementation are open questions. A case in point is Japan's Tokai plutonium fuel production facility (PFPF) where MOX fuel has been fabricated for Japan's Joyo and Monju fast breeder reactors since 1988.

The PFPF's production line consists of 17 interconnected glove boxes monitored by unattended, tamper-proof instruments, such as neutron coincidence counters. Following an April 1994 inspection conference with the IAEA, Japanese sources disclosed that approximately 70 kg of plutonium was 'held up' in the remotely monitored process line, and that the uncertainty in the NRTA system's measurement of this hold-up material exceeded at least 8 kg, enough material for several nuclear explosive devices. PNC agreed to design new glove boxes that reduce the amount of plutonium deposited in the process line, but astonishingly the IAEA did not order the shutdown of plant and an immediate clean-out inventory.

Given that 2–3 kg is sufficient for a kiloton yield weapon made from reactor-grade plutonium, the IAEA's intervention was technically four years too late to provide timely warning of a theft or diversion, should an eventual physical inventory demonstrate that kilogram quantities of plutonium remain unaccounted for. This initial application of NRTA, and the IAEA's sluggish response to the difficulties encountered, hardly inspires confidence in the future successful implementation of NRTA techniques in larger and more complex facilities with vastly greater flows of material.

In a recently published analysis of safeguards, the US Congressional Office of Technology Assessment observed:

> 'To date, the IAEA has not considered the possibility that it cannot safeguard large facilities such as the Rokkasho reprocessing plant, but neither has it demonstrated that it can.[11]

(f) Ensure efficient allocation of scarce capital resources for energy development

In the United States in the 1960s the prevailing view in the commercial nuclear industry was that the cost of civil

Table 3. Fuel cycle economics – projections against reality

1969 projections (in constant 1969 $)		
	1969	2020
Uranium price ($/lb U_3O_8)	8	50 (without breeders)
Reprocessing ($/kgHM)	37	20
Reality (in constant 1995 $)		
	1969	1995
Uranium Price ($/lb U_3O_8)	32	10
Reprocessing ($/kgHM)	150	900–2700&

spent fuel reprocessing would be relatively low, and that substantial cost savings could be realized recovering plutonium and uranium and recycling these materials in lieu of mining and enriching additional uranium. This view was also shared by nuclear industry officials in other Western countries and the Soviet Union. In 1969, for example, the US Atomic Energy Commission (USAEC) prepared a cost-benefit analysis of the US breeder reactor programme.[12] In this analysis the USAEC estimated that the cost of reprocessing civil LWR fuel would be $37.30 per kg of heavy metal (kgHM) initially.[13] Projecting that the reprocessing industry would grow in size, the USAEC estimated that reprocessing costs as a consequence of economies of scale would drop to $19.70/kgHM by the year 2020.[14] Due to inflation, these costs in today's (1995) US dollars are four times higher, or about $150/kgHM initially and $80/kgHM in 2020.

Also, in 1969 the USAEC estimated that the electrical energy demand and growth in nuclear power use would be so great that without the introduction of breeder reactors, low-cost uranium resources would be depleted and uranium prices would climb from $8/lb to $50/lb U_3O_8 ($17.6/kg to $110/kg).[15] In today's US dollars these prices would be $32/lb and $200/lb ($70/kg and 440/kg), respectively.

It transpired, however, that the cost projections of the USAEC were completely wrong. The cost of spent fuel reprocessing went up instead of down, and the cost of uranium after peaking at $44/lb U_3O_8 ($20/kg) in 1979, went down instead of up (Table 3). For example, today in the West, estimates of the cost of spent fuel reprocessing (exclusive of charges for long-term high-level waste storage, transportation, and burial) range from $750/kgHM to $1800/kgHM.[17] Cogema and BNFL reportedly charged their customers about $1400/kgHM to $1800/kgHM to subsidize construction of their respective plants at La Hague and Sellafield.[17] BNFL is said to be charging about $900/kg for contracts that would cover the second ten-year operating period of its THORP plant at Sellafield.[18] Spot prices of uranium are now $7.25/lb to $10.50/lb U_3O_8 ($16/kg to $23/kg) (Fig. 2). Thus, in the West since 1969 the cost of reprocessing in constant dollars has increased sixfold or more, whereas the cost of uranium has gone down by a factor of 3. The economic benefits of reprocessing and plutonium recycle never materialized.

It is enlightening to compare the cost of using plutonium as a MOX fuel in existing thermal reactors with the cost of low enriched uranium (LEU) fuel for the case where plutonium is treated as free goods. This would be the case, for example, were the United States to offer its excess plutonium from weapons to utilities free of charge. Table 4 compares the cost of LWR fuel made from low enriched uranium fuel with the cost of MOX made from free plutonium. Because of the high cost of MOX fabrication, as seen from Table 4, it is uneconomical to use MOX fuel in LWRs even if the plutonium is free. The cost penalty is even higher if costs are incurred for converting the plutonium from metal to oxide (PuO_2), as would be the case with plutonium from weapon components.

Table 5 compares the LEU and MOX fuel cycle costs where the plutonium for the MOX fuel is recovered by reprocessing spent fuel from conventional power ('thermal') reactors. Table 5 represents the special case where

*Table 4. Economic comparison of LWR fuels – assuming free plutonium (1995 US dollars per kilogram of heavy metal in fresh fuel)**

LEU fuel (4.4% U–235)		MOX fuel (4.8% Pu)	
Uranium as UF_6	330 ± 125†		
Enrichment services	650 ± 40‡		
Fuel fabrication	225 ± 30	Fuel fabrication	1500 ± 300
Total	1200 ± 135	Total	1500 ± 300

$1 US ≈ £0.65 ≈ 0.8 Ecu

*Sources: Holdren, J.P. *et al.* '*Management and Disposition of Excess Weapons Plutonium – Reactor Related Options.* National Academy of Sciences, Washington, D.C., 1995, 280–298; Chow B.G. and Solomon K.A. *Limiting the Spread of Weapon-Usable Fissile Materials*, RAND, Santa Monica, CA., 1993, 32–37.

†Assuming the enrichment plant operates at 0.2% tails assay and assuming 1.5% losses in chemical conversion, in order to produce one kgHM of 4.4%-enriched fuel, 9.84 kg of U_3O_8 (= 8.344 kgU must be obtained), converted into uranium hexafloride (UF_6), and then the uranium enriched from its natural level (0.711% U–235) to 4.4% U–235. The calculation assumes a uranium yellowcake price of $(40 ± 15)/kgU, and conversion costs of $(9 ± 1)/kgU.

‡Assuming the enrichment plant operates at 0.2% tails assay, in order to produce one kgHM of 4.4%-enriched fuel, 7.46 kg SWU is required. The calculation assumes the price of enrichment services is $(87 ± 5)/kg SWU. Current SWU spot-market price is $82/kg SWU to $92/kg SWU (August 1995).

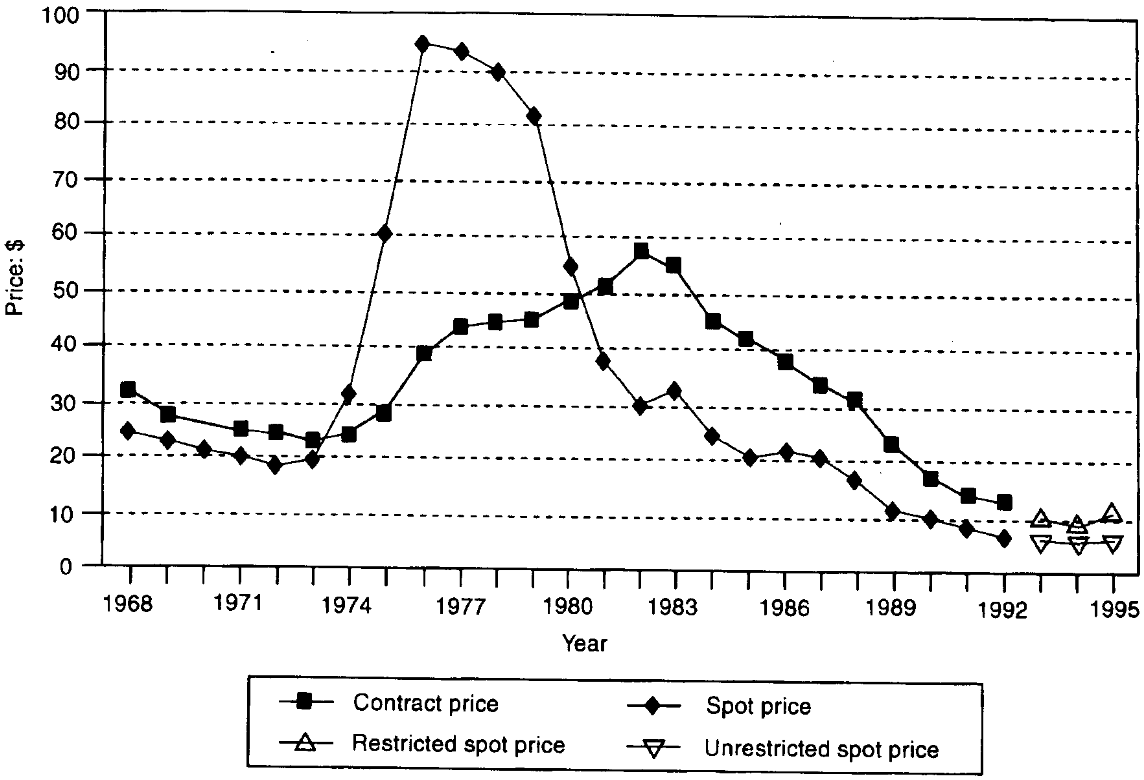

Fig. 2. Spot and delivered contract price for uranium in 1994 dollars

all of the capital investment has been met by advanced payments for separate reprocessing contracts, and therefore the cost of reprocessing is limited to the operating and maintenance cost. This case more closely represents the second 10-year tranche of reprocessing contracts at THORP in that two-thirds of the capital investment in THORP reportedly has already been met. Table 5 also takes an optimistic approach to the reprocessors by increasing the cost of natural uranium from $40/kgU (assumed in Table 4) to $60/kgU, and increasing the cost of enrichment from $85/kg SWU to $100/kgSWU. As indicated by Table 5, MOX fuel becomes even less competitive if the costs of reprocessing have to be borne. Even if the reprocessing plant capital investment cost has already been met, the cost of a MOX fuel from plutonium recovered by reprocessing is about twice the cost of an open cycle.

Table 5 shows the added cost necessary to recover the capital investment of the reprocessing plant. The first case, based on the UK THORP reprocessing plant, assumes a $2.8 billion construction cost, 25-year plant life, and 700 tons of annual throughput. The estimated cost to construct the Rokkasho plant in Japan, which has the same capacity as THORP, has recently increased from $7.5 billion to $10–20 billion, some 3.6 to 7.1 times what we have assumed for THORP.

In sum, the closed fuel cycle cannot compete with the open cycle – not now, nor in the foreseeable future.

Development efforts worldwide have demonstrated that closing the nuclear fuel cycle – that is, reprocessing to recover plutonium and uranium from spent nuclear fuel for use on existing thermal reactors or fast breeders – is uneconomical for the user. It is cheaper to operate existing thermal reactors using low enriched uranium fuel, and fast reactors (breeders) will remain uneconomical for the foreseeable future. The putative benefits of plutonium recycle and the plutonium breeder, associated with their ability to utilize uranium resources more efficiently, are not diminished if closure of the fuel cycle and commercial breeder development is postponed for decades, and the spent fuel from existing conventional reactors is stored in the interim. Moreover, energy security in the nuclear sector over the next several decades can be achieved more cheaply, more quickly and more reliably by stockpiling reserves of uranium.

Conclusion

Otto Frisch and Rudolph Peierls worked out the essential theory of the atomic bomb here in England in 1940. As a consequence of their work the United Kingdom established the Maud Committee, the first governmental body to study the feasibility of atomic weapons. Then the United Kingdom became a full partner with the United States in the development of the first atomic bombs. Once again we need the leadership of

*Table 5. Economic comparison of LWR fuels (1995 US dollars per kilogram of heavy metal in fresh fuel)**

LEU fuel (4.4% U–235)		MOX fuel (4.8% Pu)	
Uranium as UF_6	575 ± 170†	Reprocessing plant capital cost recovery	(see below)
Enrichment services	746 ± 150‡	Operations & Maintenance‖	3400 ± 1350
Fuel fabrication	225 ± 30	Fuel fabrication	1500 ± 300
		Pu incremental cost for storage and transport	100 ± 50
Waste disposal	750 ± 150	Waste disposal	750 ± 150
Total	2300 ± 300	Total	5750 ± 1400
$1 US ≈ £0.65 ≈ 0.8 Ecu		Reprocessing plant Capital cost recovery:	
		THORP:	2200 ± 200
		Rokkasho:	12,000 ± 5000

*See Table 4, Note *.

†See Table 4, Note †. The calculation assumes a uranium yellowcake price of $(60 ± 20)/kgU, and conversion costs of $(9 ± 1)/kgU. The average EURATOM contract price for natural uranium was $20.25/lb U_3O_8 ($52.64/kgU) in 1994.

‡See Table 4, Note ‡. The calculation assumes the price of enrichment services is $(100 ± 20)/kg SWU. Current SWU spot-market price is $82/SWU to $92/SWU (August 1995).

In the United States the utilities must pay the Federal Government $0.001 per kilowatt-hour of nuclear energy generated to cover the cost of the geological disposal of spent fuel. For a 1000 MWe power plant operating at 70% capacity, 32% thermal efficiency, and a fuel burnup of 40 MWd/kgHM, this represents an annual payment of $6.132 million and an annual spent fuel discharge of 20 tHM/y, or $300/kgHM of spent fuel discharged exclusive of carrying charges, or about $20 billion available for the construction of a 70,000 tHM repository. Interim dry cask storage is conservatively assumed to equal this amount, therefore $600/kgHM is taken as a lower limit. It is argued that due to mismanagement of the high level radioactive waste repository, the US Government's waste fund is too low. Therefore as an upper limit, the cost of final storage is doubled.

‖ A price of $900/kgHM has reportedly been offered for reprocessing at La Hague (France) and Sellafield (UK) after the year 2000, down from the $1400–1800/kgHM for current contracts. The drop in price may well result from the calculation that most of the capital costs will have been recovered by then. A charge of $900/kgHM becomes a reasonable upper bound for future O&M costs. The lower bound is derived by subtracting the reported capital cost component for THORP (about $450/kgHM) from the post-2000 offered price, yielding $450/kgHM. The average price is then converted to $/kgHM in spent fuel using the same method as for the capital cost assuming that 4.6 to 5.3 kgHM of spent fuel must be processed to recover the plutonium needed to make one kgHM of fresh MOX (4.8% Pu).

the United Kingdom, this time to preserve the option of ridding the world of nuclear weapons. As one of the five declared nuclear-weapon states and a member of the UN Security Council, the United Kingdom could take the first bold step and give up its nuclear weapons. If this step proves too difficult politically, there are several less bold initiatives that would further the disarmament process. The United Kingdom, for example, could simply remove its deployed nuclear warheads far from the delivery systems and place them in secure storage.

While the United States is trying to return its military plutonium and that of Russia back into spent fuel, the United Kingdom is busily removing weapon-usable plutonium from spent fuel, a programme that only undermines efforts to dispose of the military stocks.

The road to the abolition of nuclear weapons will surely be blocked if the United Kingdom, France, Russia and Japan continue to insist on pursuing the widespread commercial use of weapon-usable fissile materials under an international safeguards regime that is incapable of providing the timely detection of the diversion of these materials for military use.

At the dawn of the nuclear age, the authors of the famous Acheson–Lilienthal plan for international control of atomic energy clearly recognized the inherent military potential of fissionable materials used for avowedly peaceful purposes. From the technical standpoint, a more effective approach to blocking further proliferation would be a universal ban on the production, transfer, acquisition, or isotopic enrichment of separated plutonium, and on the isotopic enrichment of uranium to greater than 20% U-235. Alternatively, such activities could be banned when conducted under national or most multinational auspices, but permitted if conducted by a UN chartered international authority under the direct control of the UN Security Council.

The United Kingdom and other nations having or planning civil nuclear energy programmes with closed fuel cycles could make an important contribution to the nuclear disarmament process by voluntarily deferring further separation of plutonium until at least the following three conditions are met: (*a*) the existing global inventories of separated plutonium, including military stocks, are radically reduced (*b*) effective international institutions and technical controls are in place that will permit civil plutonium use without adding significantly to the risk of nuclear weapons proliferation (*c*) use of plutonium in the nuclear fuel cycle represents an economically rational investment of scarce public and private capital for energy development, in free and open competition with other energy resources.

Further enrichment of uranium above about 20% U-235 also should be curtailed, and existing stocks of HEU should be blended promptly with natural or depleted uranium to obtain low enriched uranium for reactor fuel.

Acknowledgements

I wish to thank my colleague Christopher E. Paine for his considerable contribution to this report and Robert S. Norris and Drew Caputo for their reviews and comments.

References

1. COCHRAN, T.B. *U.S. Inventories of Nuclear Weapons and Weapon-Usable Fissile Material*, NRDC Nuclear Weapon Databook Series, Revised 26 September 1995.
2. DIAKOV A.S. *Disposition of Separated Plutonium: an Overview of Russian Program*, paper presented at the Fifth International Conference on Radioactive Management and Environmental Remediation, Berlin, Germany. 3–8 September, 1995.
3. COCHRAN T.B., NORRIS R.S. and BUKHARIN O.A. *Making The Russian Bomb: From Stalin to Yeltsin*, Boulder, Westview Press, 1995, Appendix C.
4. COCHRAN T.B. *et al. Making the Russian Bomb*, p. 31.
5. FETTER S., COCHRAN T.B., GRODZINS L., LYNCH H.L. and ZUCKER M.S. Gamma Ray Measurements of A Soviet Cruise Missile Warhead, *Science*, 18 May 1990, 828–834.
6. ALBRIGHT D., ARKIN W.M., BERKHOUT F., NORRIS R.S. and WALKER W. *Inventories of Fissile Materials and Nuclear Weapons, SIPRI Yearbook 1995: Armaments, Disarmament and International Security*, Oxford University Press, Oxford, 317–336.
7. *Ibid* 323.
8. HILLS C.R., PEASE R.E., PEIERLS R.E. and ROTBLAT J. *Does Britain need nuclear weapons*. British Pugwash Group, 1995.
9. COMMITTEE ON INTERNATIONAL SECURITY AND ARMS CONTROL, *Management and Disposition of Excess Weapons Plutonium*, National Academy of Sciences, National Academy Press, Washington, D.C., 1994, Prepublication Copy, 37.
10. GILINSKY V. *Plutonium, Proliferation and Policy*, Commissioner, Nuclear Regulatory Commission, Massachusetts Institute of Technology, November 1, 1976, Press Release No. S–14–76.
11. *Nuclear Safeguards and the International Atomic Energy Agency*, OTA–ISS–615, Washington, D.C., June 1995, 73.
12. US ATOMIC ENERGY COMMISSION. *Cost-Benefit Analysis of the U.S. Breeder Reactor Program*. WASH 1126, April 1969.
13. *Ibid.*, 68.
14. *Ibid.*
15. *Ibid.*, 70.
16. CHOW B.G. and SOLOMON K.A. *Limiting the Spread of Weapon-Usable Fissile Materials*, RAND, 1993, 33–34.
17. *Ibid.*
18. *Ibid.*