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Proliferation and the nuclear disarmament process

Thomas B Cochran
Natural Resources Defense Council Inc, 1350 New York Avenue, NW, Suite 300, Washington, DC 20005, USA

The greatest nuclear proliferation risk today arises from the lack of adequate physical protection, control and accounting of weapon usable materials in Russia. The most effective way to improve physical security and material accounting in Russia is through a cooperative effort to construct a comprehensive, non-discriminatory regime that ultimately would place all nuclear weapons and nuclear weapon usable materials under some form of multilateral monitoring. There is an urgent need for government action in states that now have significant programs involving the commercial use of nuclear weapon usable materials to defer further separation of plutonium until the global inventory of separated plutonium is significantly reduced and energy market conditions fully justify the added security risks of using plutonium in the civil fuel cycle.

Keywords: Nuclear proliferation; Civil fuel cycle; Government action

There are about 30 000 nuclear warheads remaining on the territory of the former USSR, about 1000 tonnes (t) of weapon usable highly enriched uranium (HEU), about 160 t of separated plutonium in weapons or available for weapons and about 30 t of separated civil plutonium stored in Russia. Most, if not all, of these inventories are stored under inadequate conditions of physical security and material control and accounting.

Russian President Boris Yeltsin has said that 40% of individual private businessmen and 60% of all Russian companies have been corrupted by organized crime. Reports of illegal activities in Russia associated with nuclear materials – offers to sell and successful and unsuccessful attempts to steal nuclear materials – are now appearing regularly in the Russian and European press. On average there is about one new case per week. Low enriched uranium fuel has been stolen. Four tonnes of beryllium and a small quantity of HEU, thought to be less than 1 kg, was stolen from a Russian nuclear facility, perhaps Obninsk. These materials were recovered last year by Lithuanian authorities in Vilnius. This may be the case involving the theft of several hundred grams of HEU that has been confirmed by the Russian Ministry of Atomic Energy (Minatom).

In another case a Russian nuclear scientist from the Luch Production Association, which manufactures nuclear space reactors, was apprehended in October 1992 at the Podolsk train station with 1.5 kg of HEU in his suitcase. Between 10 May and 12 August 1994 German authorities intercepted four small samples of weapon usable materials, one having 300–350 g of plutonium. These are some of the cases we know about because the materials were intercepted. We know for certain that kilogram quantities of weapons usable materials are being stolen from Russian nuclear institutions, and that some of it has crossed international borders. There may have been other diversions of nuclear weapons usable materials that were successful and have gone undetected.

Corruption is rife in the Russian army; approximately 3000 officers have been disciplined for engaging in questionable business practices and 46 generals and other officers face trial on criminal charges, according to a 1993 US Department of Energy report. In 1992 some 40 000 charges of corruption were brought against members of the Russian armed forces. The Russian defense ministry has reported 4000 cases of theft of conventional weapons from military depots this year, and nearly 6500 cases in 1993 (*Economist*, 1994).

Russian storage capacity designed for nuclear warheads is inadequate to secure the inventory of nuclear warheads that have been returned to Russia from other former Soviet republics. Many nuclear warheads are now being stored in facilities constructed for the storage of conventional munitions under less than adequate physical security. Some Special Operations (*Spetsnaz*) units of the Russian military are trained in how to use atomic demolition munitions (ADMs) and have the knowledge, skills and in some cases access to nuclear weapons storage depots. Current and former *Spetsnaz* soldiers, either for profit or political reasons, could steal ADMs or other easily transportable tactical nuclear weapons. As evidenced by the illegal traffic in conventional munitions, it is rather easy to smuggle weapons stolen from a storage depot in Russia across the border into Poland, or some other East European country, and from there via a third party to anywhere in the Middle East.

The authority of the central government in Moscow is erratic and uncertain. There is only limited rule of law. Political authority is often ignored. President Boris Yeltsin is increasingly currying favor with ultra-nationalist factions. Colonel Vladimir Zhirinovsky or another hard-line nationalist may be the next president. In order to retain power the next Russian president may seek a more hostile political relationship with the West in order to strengthen the military and turn attention away from a failing economy. Nuclear arms reductions may be halted or reversed.

As a consequence of the end of the Cold War, some 1500–2000 nuclear warheads are being retired annually in the USA and Russia. Tens of tonnes of plutonium and HEU are being removed from these retired weapons annually, and an even larger and growing surplus of plutonium is being separated from civil nuclear power reactor spent fuel in Europe and Japan. In both the military and civil sectors, neither the countries involved, nor the IAEA, are able to provide adequate material accounting of plutonium inventories at most of the facilities involved in the chemical separation of plutonium and the manufacture of weapons components or civil mixed oxide (MOX) (plutonium and uranium oxide) nuclear fuel. At present there is no way to determine through material accounting procedures alone whether weapon quantities of plutonium are being diverted from these military and civil bulk handling facilities.

At the same time we have witnessed efforts by Iraq and North Korea to gain nuclear weapons in violation of their Non-proliferation Treaty (NPT) and International Atomic Energy Agency (IAEA) obligations. The nuclear intentions of Iran are suspect and the long-range plans of other countries, such as Algeria, South Korea, Taiwan and Japan are also of concern.

Given these substantial nuclear proliferation risks, strengthening the international safeguards regime and broadening its coverage to include weapon states should be among the highest, if not *the* highest, national security priority of almost every nation. The safeguards regime of the 21st century must be universal, comprehensive and non-discriminatory. Comprehensive implies coverage of all nuclear weapons and weapon usable fissile material.

Among other things, a comprehensive nuclear non-proliferation regime would:

(1) seek deep reductions in the arsenals of all nuclear weapon states, declared and undeclared;
(2) achieve a universal, global fissile material control regime with the minimum objective of having retired weapons and weapon components subject to some type of monitoring, and other fissile materials stored under international safeguards, such as those of the IAEA;
(3) seek to cap and draw down the world inventories of weapons usable fissile materials; achieve a global, verified cut off in the production of fissile materials for weapons purposes with safeguards over fissile material production facilities; and
(4) actively discourage and seek a moratorium on programs for the civil production and use of separated plutonium and HEU, with particular emphasis on programs in Russia, Japan, UK and France. The objective here is a complete ban on civil production, stockpiling and use of weapons usable fissile materials, with verified declarations and reductions of existing stocks, until such time as world energy market conditions justify the added security risk of using plutonium fuels.

Each of these objectives is discussed separately below.

Deep reductions in the arsenals of all nuclear weapon states

There are at least four barriers, or potential barriers, that must be overcome in order to achieve deep reductions in the global nuclear weapon arsenals:

(1) the disarmament process to date is viewed by many Russian experts as giving the USA a nuclear advantage;
(2) the US and Russian militaries may wish to retain large reserve warhead inventories as a hedge against breakout by the other party;
(3) nations with smaller nuclear forces may be reluctant to enter the disarmament process unless the warhead destruction process by other nuclear powers has been made completely transparent; and

(4) nuclear weapon states will be unwilling to meet deep reduction targets for nuclear weapon destruction or fissile weapon components if other countries retain large stocks of weapon-usable fissile materials for civil use.

With regard to the first barrier, there is a widespread view among Russian experts that the START II Treaty unfairly favors the USA. Consequently, the Russian Duma appears unlikely to ratify it. The US Government has not tried to resolve the Russian concerns over fairness in order to insure ratification of START II. To date, the Clinton administration has been unwilling to engage the Russians in negotiations designed to assure ratification of START II in the context of a protocol establishing a process of further reductions to levels that are satisfactory to both sides.

With regard to the second barrier, the lowest force posture in the Pentagon's Nuclear Posture Review has more than 3000 operational strategic warheads. This is numerically equivalent to the force level of the US arsenal in the mid-1950s, but today's weapons are much superior. The Pentagon apparently wants to retain an additional few thousand strategic warheads in what is terms an 'inactive reserve'. The combined total – upwards to 10 000 warheads – corresponds to US force levels in the late 1950s, at the height of the Cold War.

With regard to the third barrier, if we want all nuclear powers to join in the disarmament process it is important to take whatever steps are needed now to establish confidence in the future that warheads and fissile inventories of the superpowers have not been secretly hidden away. This means we must have comprehensive stockpile declarations and verification of the dismantlement process, a program that currently does not exist. This leads into the next objective of the much needed comprehensive non-proliferation regime.

As deep nuclear and further conventional force reductions proceed, and international control mechanisms are built up, it should become both possible and desirable to shift the international security role of nuclear weapons from 'active' day to day deterrence of nuclear and large-scale conventional attacks to the largely 'passive' role of 'discouraging' potential proliferant nations who might be motivated by the prospect of a regional or global nuclear monopoly. This shift can be achieved initially through international commitments to 'no first use' of nuclear weapons, and through the retention of modest internationally monitored residual nuclear forces, whose size and combat readiness are steadily diminished over time.

Over the long term, as greater confidence is achieved in an international control regime and capabilities for prompt nuclear attack are eliminated, this proliferation 'discouragement' mission could be performed by secure deep underground storage of residual nuclear warhead inventories – under international monitoring – that would be remated with their delivery systems only in the event of the emergence or a serious nuclear threat to international security that justified redeployment of a nuclear deterrent force.

However, this denuclearizing vision is threatened by, among other difficulties, the accumulation of large stockpiles of separated plutonium and weapon usable expertise in nominally civil programs. We need only ask how far China, for example, might be willing to go in accepting limits on, or reductions in its nuclear weapons stockpile if Japan were to accumulate an even larger inventory of weapons usable fissile materials in pursuit of a civil plutonium program with no clear commercial rationale.

Likewise, Russia's continued operation of reprocessing plants and potentially large-scale commitment to the breeder reactor fuel cycle could abort US political support for continuing toward very deep reductions and ultimate abolition of nuclear weapons stockpile. The lack of such a commitment by the USA and other nuclear weapons states, could, in turn, lead to continued erosion of the non-proliferation regime. Hence the need to forthrightly address the (in our view) mistaken legitimacy afforded civil plutonium programs under the current system of international controls.

Placing all nuclear weapons and weapons usable materials not under some form of bilateral or international safeguards

Perhaps the greatest non-proliferation priority today is to improve the physical security and material accounting of warheads and weapons usable materials in Russia. Russian nuclear weapons material, naval fuel and civil reactor fuel facilities are highly integrated. Many of these facilities are old and cannot meet IAEA safeguard criteria. For these reasons Russian officials are unwilling to consider IAEA safeguards over these facilities at this time. Consequently, the most promising means of achieving the necessary improvements is through US–Russian and other bilateral efforts. To obtain full Russian participation, any bilateral effort must be on a completely reciprocal basis to avoid the appearance of meddling in Russia's national security affairs.

The most promising US–Russian bilateral approach would be a program designed around a joint cooperative nuclear weapons lab to lab initiative. Such an initiative needs a mission, and this mission should be to construct the comprehensive non-discriminatory safeguards regime that covers all nuclear weapons and weapon usable fissile material.

Table 1 Current safeguards

	Weapon states		Non-weapon states
	Declared	Undeclared	
Military	■	■	■
Warheads	■	■	■
Operational	□	□	■
Reserve	□	□	■
Retired	□	□	■
Fissile material	■	■	■
In warheads	□	□	■
Reserved for warheads	□	□	■
Declared excess	□	□	■
Facilities	■	■	■
Weapon production	□	□	■
Material production	□	□	■
Excess material storage	□	□	■
Naval fuel cycle	■	■	■
Facilities	□	□	□
Fuel	□	□	□
Civil nuclear	■	■	■
Reactors	□	IAEA	IAEA
Fuel cycle facilities	□	IAEA	IAEA
HEU/Pu	□	IAEA	IAEA
LEU	□	IAEA	IAEA
Spent fuel	□	IAEA	IAEA

Table 2 Fissile cut off for weapons and excess stocks under IAEA safeguards

	Weapon states		Non-weapon states
	Declared	Undeclared	
Military	■	■	■
Warheads	■	■	■
Operational	□	□	■
Reserve	□	□	■
Retired	□	□	■
Fissile material	■	■	■
In warheads	□	□	■
Reserved for warheads	□	□	■
Declared excess	IAEA	■	■
Facilities	■	■	■
Weapon production	□	□	■
Material production	IAEA	IAEA	■
Excess material storage	IAEA	■	■
Naval fuel cycle	■	■	■
Facilities	□	□	□
Fuel	□	□	□
Civil nuclear	■	■	■
Reactors	□	IAEA	IAEA
Fuel cycle facilities	IAEA	IAEA	IAEA
HEU/Pu	IAEA	IAEA	IAEA
LEU	□	IAEA	IAEA
Spent fuel	□	IAEA	IAEA

In the left-hand column of Table 1 are listed various categories of nuclear weapons, fissile materials and weapons and fissile material facilities. The second column denotes the declared weapons states – the USA, UK, Russia, France and China. The third column denotes the undeclared weapons states – Israel, India and Pakistan; and the last column denotes the non-weapon states. As seen from Table 1, all of the nuclear weapons and most of the fissile material facilities are not covered by the IAEA or even bilateral safeguards. As shown in Table 2, even with the Clinton administration objectives of a global cut off in the production of fissile material for weapons, and with IAEA safeguards placed over fissile materials declared 'excess' to national security requirements, all nuclear warheads and many fissile material inventories and production facilities will remain

Table 3 A comprehensive safeguards regime for the 21st century

	Weapon states		Non-weapon states
	Declared	Undeclared	
Military			
Warheads			
Operational	Monitored		
Reserve	Monitored		
Retired	Monitored		
Fissile material			
In warheads	Monitored		
Reserved for warheads	Monitored		
Declared excess	IAEA	IAEA	
Facilities			
Weapon production	Monitored		
Material production	IAEA	IAEA	
Excess material storage	IAEA		
Naval fuel cycle			
Facilities	Monitored	Monitored	Monitored
Fuel	Monitored	Monitored	Monitored
Civil nuclear			
Reactors	IAEA	IAEA	IAEA
Fuel cycle facilities	IAEA	IAEA	IAEA
HEU/Pu	IAEA	IAEA	IAEA
LEU	IAEA	IAEA	IAEA
Spent fuel	IAEA	IAEA	IAEA

outside any bilateral or international safeguards, including the weapons usable material inventories in Russia. As we move into the 21st century, what is needed is a comprehensive regime covering all nuclear weapons and weapon usable materials (Table 3).

A logical first step would be for the USA to engage the Russians in a comprehensive reciprocal of exchange of data related to warheads and weapons usable fissile material. Such a data exchange, if accompanied by agreed measures to verify it, including isotopic fingerprinting of materials in storage, would:

- let us know what the Russians have and where it is;
- allow us to independently tell whether weapons and weapons usable fissile material have been diverted;
- allow us to determine the source of diverted material once intercepted; and give us a better assessment of what improvements are needed with respect to Russian physical security and material accounting programs.

On 12 February 1992 Foreign Minister Andrei Kozyrev formerly proposed a reciprocal data exchange among all nuclear nations on inventories of nuclear weapons and fissile materials, and on nuclear weapons production, storage and elimination facilities. None of the other nuclear weapons states responded positively to this initiative, or offered constructive alternative proposals. In the USA the principal problem was opposition, primarily by the Pentagon, to reciprocal inspections of US nuclear weapons and facilities by the Russians. In a similar vein, the USA, UK and France recently quashed a German initiative to add nuclear weapons to a UN registry of conventional arms, and even opposed a registry limited to warheads that had been dismantled.

It is perhaps worth noting that the West does not know within thousands how many nuclear warheads the Russians have. We do not know within hundreds how many warheads are dismantled annually. We do not know within tens of tons how much plutonium the Russians have produced, or within hundreds of tons how much HEU the Russians have produced. Had Kozyrev's data exchange proposal been implemented in a comprehensive manner, German authorities could have immediately narrowed down, if not determined, the sources of the three small samples of plutonium and one small sample of HEU seized between May and August of this year.

In June of this year the Pentagon, prodded by the Department of Energy, agreed – at least in principle – to propose to the Russians a bilateral data exchange, and some yet to be defined verification measures, covering all warheads, except operational and inactive reserve warheads, and all fissile materials. In other words, the prospective data exchange and verification measures would cover those warheads awaiting dismantlement and those being dismantled, and the fissile materials recovered from dismantled warheads and in civil stocks. While such an agreement in principle has not yet been developed into a concrete proposal to the Russians, we can anticipate some positive developments in this area at the Clinton–Yeltsin summit at the end of this month in Washington, DC. Continued efforts to restrict Russian access to US facilities, and vice versa, are likely to severely curtail any bilateral verification measures.

Capping and drawing down the stocks of weapons usable materials

The US government has undertaken four initiatives toward this end: purchase by the USA of Russian HEU; assistance in cutting off the production of weapon grade plutonium; promotion of an international convention banning the production of fissile materials for weapons; and placing small stocks of plutonium and HEU, declared 'excess' of national security requirements, under IAEA safeguards.

With respect to the first initiative, the USA stopped production of HEU for weapons in 1964. The USA has agreed to purchase 500 t of HEU from Russia which will be blended down into low enriched uranium in Russia. By failing to engage the Russians in a data exchange, the US government does not know what fraction of the total Russian HEU inventory it is purchasing. The HEU purchase agreement includes a recently negotiated protocol that was meant to detail how the USA could be assured that the HEU was derived from Russian weapons, and how Russia could be assured that its material would be used only for peaceful purposes. The transparency protocol negotiated by the administration may permit the USA to confirm that the uranium was HEU, but it apparently does not permit the USA to confirm that the HEU actually is from dismantled weapons. Moreover, Russia continues to produce HEU for 'non-weapons purposes', in effect replacing the HEU being sold to the USA.

With respect to ending Russian production of plutonium for weapons, the USA was slow to respond to a Russian request for assistance. The Clinton administration did not get serious until the US Congress made funding for new plutonium storage facilities in Russia conditional on a serious commitment to halt plutonium production for weapons. Although three separate agreements were subsequently concluded by various US and Russian government officials – the last by Vice President Gore and Prime Minister Chernomyrdin – the commitment to shut down the three remaining plutonium production reactors in Russia is stalled because no source of funding for replacement power has been identified and because of Minatom's insistence that the replacement power be nuclear. It is also noteworthy that the agreements exclude two other production reactors in Russia that are used for tritium and plutonium 238 production, and it excludes the chemical separation facility that processes the spent fuel from these reactors.

Half of the plutonium separated in Russia today is chemically separated at this facility, which is also used to process spent naval and civil reactor fuel. The Russians refuse to include this chemical separation plant in a bilateral safeguards agreement, on the grounds that the USA refuses to permit reciprocal oversight over US naval reactor fuel. Moreover, in an effort to get Minatom to consider a broader safeguards agreement, US negotiators assured the Russians that the US government would not use a future broader agreement as a means to halt civil reprocessing in Russia. Meanwhile Minatom has persuaded President Yeltsin to commit 500 thousand million roubles to complete the RT-2 chemical separation plant at Krasnoyarsk-26 to reprocess VVER 1000 and foreign reactor spent fuel. If the Russian government perseveres with this commitment, it will only exacerbate the difficulties with a national safeguards regime that is already leaking like a sieve.

With respect to the third initiative, negotiations of a convention banning the production of fissile material for weapons are now under way at the CD in Geneva. Given the large surpluses of weapons materials in the declared nuclear weapons states, the benefits of the effort ultimately will depend upon whether India, Pakistan and Israel join such a convention. At this stage there is no hard evidence that they will.

Although the USA is proceeding with plans to place excess weapons plutonium and HEU under IAEA safeguards, only 10 t of HEU will be placed under IAEA safeguards initially, owing to the navy's desire to retain most of the surplus HEU for its own use. No decision has been made with regard to how much plutonium will be placed under IAEA safeguards.

A moratorium on programs for the civil production and use of separated plutonium and HEU

Table 4 lists six reasons for deferring further chemical separation of plutonium for use in the civil nuclear fuel cycle. Each of these arguments is reviewed separately below.

Small amounts of plutonium are required for a nuclear weapon

After almost a half century of living with nuclear weapons there is still considerable misinformation about the fissile material requirements for nuclear weapons. For single-state pure fission weapons, a spherically symmetric implosion design requires the least amount of fissile material to achieve a given explosive yield, relative to other possible designs. For this type of device the amount of fissile material required depends primarily upon the type of fissile material used, eg plutonium, U 233 or HEU, the desired explosive yield of the device, and the degree to which the fissile material is compressed when the disassembly of the fissile material begins as a result of the release of energy from the rapid

Table 4 Reasons for deferring further chemical separation of plutonium in the civil nuclear fuel cycle

1. **Improve chances for human survival**
   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.
2. **Limit spread of nuclear explosive material**
   National separation, recycling and breeding of plutonium on a commercial scale place an impossible burden on the current capabilities of the IAEA safeguards system to detect promptly thefts or diversions of Pu bomb quantities from peaceful use.
3. **Prevent abuse of nuclear technology**
   'Civil' plutonium programs provide a legitimate civilian cover for any country to acquire a stockpile of nuclear explosive materials, while sustaining a global technoogy base in chemical separation, processing and metallurgy that has been – and will continue to be – applied to clandestine military programs.
4. **Reduce potential for NPT 'breakout'**
   Nations that have 'legally' acquired a stockpile of separated plutonium, under safeguards, but then undergo political upheaval, may emerge as nations determined to build nuclear arsenals.
5. **Encourage destruction of weapon stocks**
   Stockpiles of separated 'civil' plutonium and operational Pu production facilities will act as a barrier to deep reductions and eventual elimination of nuclear weapons held by declared and undeclared nuclear weapon states.
6. **Insure efficient allocation of capital resources**
   Separation and use of plutonium in the civil nucelar fuel cycle is not justified now by current or foreseeable energy market conditions, which favor investments in conservation, efficiency and a range of competing power sources, including safer, more reliable and efficient advanced LWR technology.

Table 5 Approximate fissile material requirements for pure fission nuclear weapons

	Weapon grade plutonium (kg) Technical capability			Highly enriched uranium (kg) Technical capability		
Yield (kt)	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
1	3	1.5	1	8	4	2.5
5	4	2.5	1.5	11	6	3.5
10	5	3	2	13	7	4
20	6	3.5	3	16	9	5

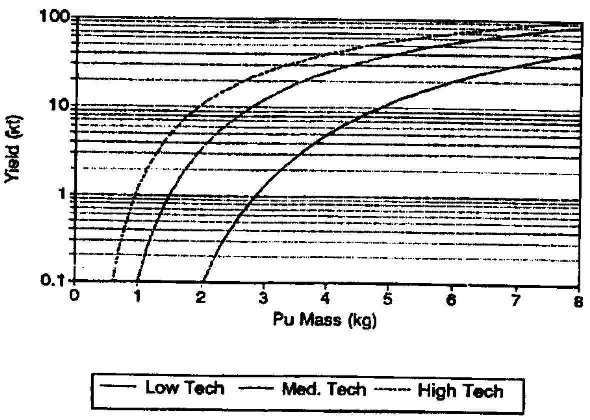

Figure 1 Yield versus Pu mass (as a function of technical capability)

nuclear chain reaction. The degree of compression achieved depends on the sophistication of the design and degree of symmetry achieved by the imploding shock wave. There are, of course, other factors – such as the timing of the initiation of the chain reaction and the type of neutron reflector used – but we will assume that the proliferant state or subnational group already has acquired the necessary skills so that these factors are of secondary importance.

Figure 1 is a graph showing the explosive yield of a pure fission weapon as a function of the quantity of weapon grade fissile material for three degrees of compression. In the figure the degree of compression is labelled according to our judgement as to the sophistication of the design; that is, whether it represents low, medium or high technology. As seen from Figure 1, the Nagasaki bomb, *Fat Man,* which produced a 20 kt explosion with 6.1 kg of WGPu, falls on the low technology curve. However, only 3 kg of WGPu compressed the same amount would still have produced a 1 kt explosion. A 1 kt yield is still a very damaging explosion with the potential to kill tens of thousands of people, depending on the population density and physical characteristics of the targeted area. Many tactical nuclear weapons that were in the US nuclear arsenal had yields in the kiloton, and even subkiloton range.

But the bad news does not stop there. A non-nuclear weapons state today can take advantage of the wealth of nuclear weapons design information that has been made public over the past 50 years, and do even better. As seen from Figure 1, to achieve an explosive yield of 1 kt, we estimate that from 1 to 3 kg of WGPu is required, depending upon the sophistication of the design. We also estimate that some 2 to 7 kg of HEU is required to achieve an explosive energy release of 1 kt. Table 5 presents some of the results of our calculations in a different form. We estimate, for example, that as little as 2 kg of plutonium, or about 4 kg of HEU, is required to produce a yield of 10 kt.

The curves in Figure 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%. The critical mass of reactor grade plutonium falls between that of weapon grade plutonium and HEU.

Plutonium with a high Pu 240 content is less desirable for weapons purposes than weapon grade plutonium, because for low technology weapons designs the neutrons generated by the high rate of spontaneous fission of Pu 240 can increase the statistical uncertainty of the yield by 'pre-initiating' 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 USA, based in part on a classified 1994 study by scientists at the Lawrence Livermore National Laboratory (Committee on International Security and Arms Control, 1994, p37):

> 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.

By making use of various combinations of advance 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 Pu240. NRC Commissioner Victor Gilinsky best summed up the issue in 1976, when he stated, (Gilinsky, 1976):

> 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.

IAEA safeguards and physical security measures provide insufficient insurance against proliferation

Adequate physical security is essential to prevent the theft of any quantity of material, even as little as one bomb's worth. Highly accurate material accounting and control measures are essential to determine whether a theft has taken place, and to provide timely warning to prevent the material from being used for illicit purposes. It is well established – from experience at existing civil and military chemical separation (reprocessing) plants, naval fuel facilities, and MOX fuel facilities – that it is extremely difficult (some would argue 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 difficulty 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. 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 Russia physical security has relied on heavily guarding not only the facilities, but also the towns where the work force resides. These closed cities 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 program from outside scrutiny. It is now known that at various times in the past, the governments of the USA, Japan (during World War II), USSR, UK, France, China, Israel, India, South Africa, Sweden, Argentina, Brazil, Taiwan, Pakistan, North Korea, South Korea and Iraq have had secret nuclear weapons development programs. In light of this history, combating 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.

The international community's principal tool for penetrating the secrecy of nuclear facilities is the power of the International Atomic Energy Agency to conduct inspections and require adherence to strict material accounting and control procedures, collectively referred to as 'safeguards'. These are meant to provide timely detection of the diversion of significant quantities of weapons usable material.

Table 6 IAEA significant quantities

Material	Quantity of safeguards significance	Safeguards apply to
Direct use nuclear material		
Plutonium (<80% Pu 238)	8 kg	Total element
Uranium 233	8 kg	Total isotope
Uranium enriched to 20% or more	25 kg	U 235 isotope
Indirect use nuclear material		
Uranium (<20% U 235)	75 kg	U 235 isotope
Thorium	20 t	Total element

While there are numerous shortcomings in the design and implementation of IAEA safeguards, we focus here on three technical flaws. (1) The IAEA's 'significant quantity' (SQ) values are technically flawed – they are far too high. (2) Detection of the diversion of a SQ amount applies to a material balance area, instead of the entire facility, or even country. (3) The IAEA's timely detection criterion cannot be met.

For safeguards purposes the IAEA (IAEA, 1987, p 23) defines a 'significant quantity' (SQ) of nuclear material as 'the approximate quantity of nuclear material in respect of which, taking into account any conversion process involved, the possibility of manufacturing a nuclear explosive device cannot be excluded'. Significant quantity values currently in use by the IAEA are given in Table 6 (IAEA, 1987, p 24)

The SQ values were recommended to the IAEA by a group of experts (Shea, 1992), namely the IAEA's Standing Advisory Group for Safeguards Implementation (SAGSI), and 'relate to the potential acquisition of a first nuclear explosive by a non-nuclear weapon state'.

The direct use values in Table 6, that is, 8 kg of plutonium, 8 kg of uranium 233 and 25 kg of HEU, are also referred to by the IAEA as 'threshold amounts', defined as 'the approximate quantity of special fissionable material required for a single nuclear device' (Shea, 1992, p 23). The IAEA cites as a source for these threshold amounts a 1967 United Nations document (UN, 1967). The IAEA states,

> These threshold amounts include the material that will unavoidably be lost in manufacturing a nuclear explosive device. They should not be confused with the minimum critical mass needed for an explosive chain reaction, which is smaller.[34]
>
> [34] Using highly sophisticated techniques available to NW [nuclear weapon] States, the critical mass and the corresponding threshold amount can also be significantly reduced, but these are special cases that need not be considered here.

As seen from Figure 1, the direct use SQ or threshold values currently used by the IAEA are technically indefensible. The IAEA is making false claims as to the minimum quantity of nuclear material needed for a nuclear weapon, even for a low technology first nuclear explosive by a non-nuclear state, including consideration of unavoidable losses. If one took the same Fat Boy design, first tested at the Trinity site in New Mexico and dropped on Nagasaki in 1945, and substituted a 3 kg plutonium core for the 6.1 kg core that was used in 1945, the yield of this device would be of the order of 1 kt, a very respectable atomic bomb. Thus, the IAEA is in error to assert that 'highly sophisticated techniques available to NW States' are needed to make nuclear weapons with 'significantly reduced' quantities of materials.

The so-called 'highly sophisticated techniques available to NW States' were known to US weapons designers in the late-1940s and early 1950s, and nuclear devices using very small quantities of plutonium and HEU – so called 'factional crit' weapons – with yields of the order of 1 kt were tested during the Ranger series in 1951. Furthermore, a well advised safeguards program for a given country or group of countries would set the 'significant quantity' levels at values less than the minimum amount needed for a weapon, in recognition of the fact that materials can be diverted from more than one source. The practice of setting higher levels to account for manufacturing losses is imprudent, particularly in view of the fact that a significant fraction of these 'losses' are technically recoverable.

In sum, safeguards apply to all non-weapons countries, irrespective of their technological sophistication. Many countries, such as Japan, Germany Israel, India and Pakistan, have highly developed nuclear infrastructures, and must be considered technologically sophisticated. Even for countries that are in general not terribly sophisticated technologically, the key technical information needed to establish a program for achieving substantial compression by implosion techniques is now available in the unclassified literature. The quantities defining safeguards significance, therefore, must be based on the assumption that the proliferator has access to advanced technology. As a consequence, NRDC believes the IAEA's significant quantities should be lowered at least eight-fold to the values in Table 7.

In the parlance of nuclear material accounting the inventory difference (*ID*) is defined as

$$ID = BI + I - R - EI,$$

where BI is the beginning inventory, EI is the ending inventory, and I and R are, respectively the material added and removed during the inventory period.[1] For the minimum amount of diverted plutonium (assumed by

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[1] In the literature 'inventory difference' (ID) is sometimes called 'material unaccounted for' (MUF).

Table 7 NRDC's proposed significant quantities

Material	Quantity of safeguards significance	Safeguards apply to
Direct use nuclear material		
Plutonium (<80% Pu 238)	1 kg	Total element
Uranium 233	1 kg	Total isotope
Uranium enriched to 20% or more	3 kg	U 235 isotope

the IAEA to be the SQ value – currently 8 kg of plutonium) to be distinguished from measurement noise with detection and false alarm probabilities of 95% and 5%, respectively, it can be shown that 3.3 σ_{ID} must be less than the SQ value, where σ_{ID} is the uncertainty in the inventory difference (Miller, 1990). This means if the SQ value for plutonium were lowered to 1 kg, σ_{ID} should not exceed about 300 g.

At existing reprocessing plants in the West that handle tons of weapons usable plutonium, σ_{ID} is dominated by the error in measuring the plutonium input into the plant, which is about 1% of the throughput. The Japanese Tokai Mura plant, one of the smallest plants in the West, has an average output of about 90 t of heavy metal per year (tHM/y), and the light water reactor (LWR) spent fuel processed has an average total plutonium content of about 0.9%. Thus, σ_{ID} for Tokai Mura is about 8 kg of plutonium per annual inventory. Even if inventories were taken every six months, σ_{ID} would be about 4 kg, which is an order of magnitude too high. It is simply impossible to detect the diversion of several bombs' worth of plutonium annually from Tokai Mura.

We are told that material accounting and control at Russian plants handling nuclear fuel in bulk form is rudimentary at best. The RT-1 chemical separation plant at Chelyabinsk 65 has a capacity of about 400 tHM/y, and until 1991 had been operating at about 200 tHM/y. Therefore, the situation at RT-1 would be two to six times worse than at Tokai Mura, even if it were brought up to current Western standards.[2] It is difficult to imagine running a bank in which you counted the money only a few times a year, and then only counted the notes larger than 10 000 roubles. Yet the Russian nuclear establishment sanctions the commercial use of nuclear weapons usable material under safeguards that are no better.

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; and 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 the state is engaging 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 7–10 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 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 – virtually to zero. It would also drive up the cost of reprocessing. Plutonium recycle, the use of fuel in standard commercial LWRs, is already uneconomic 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 greater than that of the LWR operating on the once-through cycle without plutonium recycle.

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. This and similar concepts are likely to be opposed by operators, given costs that would be imposed. In any case the methods and adequacy of practical NRTA system implementation are open questions.

Preventing the abuse of civil nuclear technology

Deployment of plutonium fast breeders would entail staggering amounts of nuclear weapons usable plutonium in the reactors and the supporting fuel cycle.[3] There is

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[2] According to Evgeni Dzekun, chief engineer of the Mayak civil reprocessing plant at Chelyabinsk 65, a plutonium input-output balance for the plant is calculated every three to four months when the plant is cleaned out between reprocessing campaigns. About 1% of the plutonium is lost to waste streams, and a lesser amount to plate out in the plant's plumbing. The *ID* is typically 15 kg of Pu per campaign, amounting to a total *ID* of about 3% of throughput. In other words, the *ID* is almost twice the IAEA's significant quantity for plutonium. According to Dzekun, if the *ID* in a given campaign is larger than can be explained by measurement errors, a 'special investigation' is carried out, but what this consists of is not known. To assure detection of an 8 kg diversion at this plant with 95% confidence and a 5% false alarm rate, 3.3 × *ID* must be less than 8 kg, so this plant apparently falls short of the minimum IAEA standard by a factor of six. If 1 kg is regarded as the amount needed for a weapon, then the 'safeguards' at Mayak need to be improved by a factor of 50 in order to provide confident detection of diverted material. See Von Hippel *et al* (1992).

[3] With a plutonium breeder economy the quantity of plutonium involved would be enormous. The plutonium inventory in a commer-

no adequate means of safeguarding this material to prevent some of it from being used for nuclear weapons.

The continued development of plutonium breeders in the few remaining countries that have strong breeder research and development programs will continue to legitimize breeder programs and plutonium stockpiles in non-nuclear weapons states that may use these programs to cover the development of a weapons option. India recovered the plutonium for its first nuclear device in a reprocessing plant that was ostensibly developed as part of its national breeder program.

Consequently, remaining breeder research and development programs, if not deferred altogether, should be limited to conceptual design efforts only, with an emphasis on advanced proliferation resistant fuel cycles that no not require mastery of the technology for isolating and fabricating weapons usable nuclear materials. To the extent that this is politically impossible, sufficient plutonium has already been separated to meet the needs of R & D programs, so at a minimum there is no requirement to continue separating plutonium for this purpose. In this connection it should be noted 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 insure the possibility of deploying breeders at some point in the future.

By giving sanction to reprocessing the world is confronted with large flows of recovered plutonium and plutonium stockpiles. If only 10 GW of electric capacity were supplied by breeders – hardly enough to justify the R & D effort in any country even if the economics were otherwise favorable – the plutonium inventory in the reactors and their supporting fuel cycle would be of the order of 100–200Mt – sufficient for 17 000 to 33 000 nuclear weapons each using 6 kg of plutonium. By comparison, US nuclear weapons stockpiles in 1987 consisted of 23 400 warheads, and the weapon grade plutonium inventory, most of which was in weapons, was about 90 Mt. The Russian warhead plutonium stockpile consists of an estimated 135–170 Mt of plutonium in a total stockpile which peaked in 1985 at about 45 000 warheads.

About one half of the plutonium created in a breeder reactor is bred in the blanket rods. The burn up of the blanket material is low. Consequently, the resulting plutonium is weapon grade, with a Pu 240 concentration lower than that used in US and Russian weapons. Thus, any non-weapons country that has large stocks of breeder fuel has the capacity to produce a ready stock of weapon grade plutonium. It only has to segregate and reprocess the blanket assemblies separately from the core assemblies.

The risk of breakout

Reprocessing of spent fuel and the recycling of plutonium[4] 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. At the same time, without violating any international safeguards agreements, these countries can design and fabricate 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 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'.

Likewise, acceptance of the plutonium breeder as an energy option provides the justification for the early development of a reprocessing capability by any country. A non-nuclear weapons country would always have the option to shift its 'peaceful' nuclear program to a weapons program, but this would require the politically difficult decision to attempt evasion or overtly abrogate IAEA safeguards. Without national reprocessing facilities and breeder reactors, countries wishing to develop nuclear weapons capacity face very considerable political problems and cost. Obtaining large quantities of weapon usable plutonium requires that they build one or more specialized production reactors and chemical separation facilities. By establishing their nuclear weapons option through a plutonium using nuclear electric generation program, they can circumvent these obstacles.

Remove a potential barrier to achieving deep reductions in the global nuclear arsenals

As discussed above, stockpiles of separated 'civil' plutonium will act as a barrier to deep reductions and eventual elimination of nuclear weapons held by

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cial-size breeder is about 5 Mt, of which 3.5 Mt is fissile – sufficient for 800 atomic bombs using 6 kg of plutonium each. A Russian BN 800 breeder reactor would require over 4 Mt. Although the net amount of plutonium produced in a fast breeder reactor annually is generally less than that produced in a conventional thermal power reactor of the same size, one-third to one-half of the FBR fuel must be removed annually for reprocessing, plutonium recovery, and remanufacture into fresh fuel. Since the fuel will be outside of the reactor for 3.5 to 7 years the plutonium inventory needed to support a single commercial-size plutonium breeder is 11–22 Mt – sufficient for 1800 to 3600 atom bombs using 6 kg of plutonium each.

[4] Or any other weapons material, such as highly enriched uranium or uranium 233.

declared and undeclared weapon states. Therefore, nations having civil nuclear energy programs with closed fuel cycles can make an important contribution to the disarmament process by deferring further separation of plutonium until the global inventories of plutonium are substantially reduced.

Plutonium economics

Development efforts worldwide have demonstrated that plutonium fast breeders are uneconomical – unable to compete with thermal reactors operating on a once through uranium cycle – and that breeders will remain uneconomic for the foreseeable future. The putative benefits of the plutonium breeder, associated with its ability to more efficiently utilize uranium resources, are not diminished if commercial breeder development is postponed for decades, and the spent fuel from existing conventional reactors is stored in the interim. As thoroughly documented by Paul Leventhal and Steve Dolley of the Nuclear Control Institute in the USA, energy security in the nuclear sector can be achieved more cheaply and more quickly by stockpiling uranium.[5]

The use of plutonium in the form of MOX fuel in conventional power ('thermal') reactors is likewise uneconomic, because the costs of using MOX fuel cannot compete with those of enriched fresh uranium fuel for the foreseeable future. A recent study by the RAND Corporation in the USA estimates that, at the current cost for reprocessing services, the price of uranium feedstock for enrichment would have to increase by a factor of 16 before plutonium recycle in LWRs becomes competitive (Chow and Solomon, 1993, pp 36–38).

At current reprocessing costs and an FBR/LWR capital cost ratio of 1.5, the yellowcake price would have to increase by a factor of 45 before the breeder becomes competitive. When might this happen? The earliest date, based on the most optimistic assumptions about nuclear energy growth, reprocessing costs and breeder capital costs, is at least 50 years away, and the more likely case is 100 years away. On the timescale for technology development, a period of 50–100 years is a very long time, during which more efficient fission options may emerge, to say nothing of advanced solar and new energy technologies not yet invented.

Accumulating a plutonium inventory today is not required to insure a sufficient start up fuel supply for breeders. If the time ever comes when plutonium breeders are both economically competitive and proliferation resistant, start up cores can be made from reserves of uranium enriched to about 20% U 235 (since the critical mass of 20% enriched uranium metal is 14 times that of 93.5% enriched HEU metal, it would require of the order of 35 times, or more, 20% enriched HEU compared with the amount of weapon grade plutonium needed, and the same increase in the amount of high explosive, to achieve a comparable yield). Consequently, there is no sound economic or energy security justification for continued commercial reprocessing.

Despite these realities, however, by the end of 1990, France, the UK and Japan alone had separated about 90 t of civil plutonium, and these countries plan to separate an additional 170 t by 2000 (Albright *et al*, 1993, p 109) The global inventory of separated civil plutonium (ie not fabricated into fuel or in use in reactors) will rise to an estimated 170 t by the turn of the century (Albright *et al*, 1993, p 142), that is, almost twice the size of the US weapons plutonium stockpile at its peak. This amount would be in addition to more than 100 Mt of plutonium likely to be removed from retired US and former Soviet weapons.

Conclusion

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 fissile materials used for ostensibly peaceful purposes. Indeed, they believed that no widespread use of nuclear energy for civil purposes was possible or desirable without international ownership and control of the full nuclear fuel cycle.

Today it remains the unanimous opinion of the weapons design and arms control communities that the pacing consideration in a country's acquisition of a nuclear weapon is not the capability to design a nuclear device, but the availability of fissile materials which can be turned to weapons purposes. Ending – as opposed to 'managing' – nuclear weapons proliferation will probably prove impossible as long as production of highly enriched uranium (HEU) and chemical separation of plutonium for national security needs remain legitimate activities in a particular class of 'nuclear weapon states', and the international control regime permits civil nuclear fuel reprocessing in any state that asserts a peaceful interest in plutonium recycle and future deployment of plutonium breeder reactors for energy production.

With the end of the cold war, and the reductions in the superpower arsenals, the USA and Russia have huge surpluses of weapon grade plutonium and HEU. There is no need for additional weapons plutonium production in other declared weapons states. By completely renouncing the production, separation and isotopic enrichment of weapons usable nuclear materials, declared weapons states can put pressure on undeclared weapons states to do the same. Weapon usable fissile materials have no

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[5] See, for example, Leventhal and Dolley (1994).

legitimate application in today's energy marketplace, and can always be produced in the future should the appropriate market and international security conditions emerge.

Despite the fact that all types of plutonium in relatively small quantities, irrespective of their designation as civil or military, have an inherent capability to be used in weapons, the current non-proliferation regime allows national separation and acquisition of plutonium (and HEU) under an internationally monitored commitment of peaceful use. A more effective non-proliferation approach would be a global 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.

The heavy commitment of the UK, France, Japan and Russia to spent fuel reprocessing and recycle of plutonium, and the lingering hopes of a future revival of the plutonium fast breeder program, have effectively barred consideration of such a simple and direct step as outlawing production and acquisition of weapons usable fissile materials on a global basis.

While there are obvious technical advantages in such a comprehensive approach, tangible political progress will be more likely to be achieved in the near term by adopting *parallel* approaches that seek separate controls – in the initial stages at least – on the military and civil applications of weapon usable fissile materials.

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