Friulian Journal of Science **12.** 2009, 67-92

Scientific and technological challenges posed by the perspective of a world free of nuclear weapons

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Abstract. After many decades, nuclear disarmament has now finally moved into the mainstream of international politics. Endorsed by prominent political figures, it has become the focus of intense debate and discussion, with several institutions seriously studying approaches and possible concrete initiatives.
In its initial part, the paper recalls the most important historical steps in this direction: the 1945-6 initiatives towards international control, the *Reykjavik Meeting* and the recent *Hoover Initiative*.
The military confrontation during the cold war resulted in the creation, in several countries, of huge arsenals of nuclear weapons of different kind. In addition, exorbitant quantities of fissile materials have been produced: mostly plutonium and highly-enriched uranium (HEU), they are the essential ingredients of all nuclear weapons, their production methods posing the greatest technical challenge to nuclear specialists.
The paper provides readers with an introduction to nuclear weapons, fissile materials, their production and their use in nuclear weapons and an overview of the current levels of fissile-material stocks worldwide.
The many scientific and technical challenges facing the transition to a secure and stable nuclear-free world are then considered. These include the mechanism shaping the disarmament progress, the issue of reversibility, the management and elimination of fissile material stocks, the risks of nuclear weapon reconstitution or proliferation using materials and expertise employed in civilian nuclear energy programmes, and the definition of proper safeguards.
Specific attention is paid to the disposal of HEU, including that used for non-weapon production, in particular for naval propulsion, research reactors and medical isotope production.
The problems of separated plutonium and of its increasing stocks from civilian power reactors are underlined, together with the issue of plutonium disposal, which leave a lot of space for further research.

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The scientific community has produced numerous studies focussing on the technical aspects of nuclear disarmament, suggesting solutions and workable approaches. Yet more research and thought is needed to support a realistic approach to a world free from nuclear weapons.

Key-words. Nuclear weapons, disarmament, military research, international relations.

1. The revitalization of an old objective. On April 1st, 2009 President Dmitry Medvedev of the Russian Federation and President Barack Obama of the United States of America released this joint statement:

> We committed our two countries to achieving a nuclear-free world, while recognizing that this long-term goal will require a new emphasis on arms control and conflict resolution measures, and their full implementation by all concerned nations. We agreed to pursue new and verifiable reductions in our strategic offensive arsenals in a step-by-step process, beginning by replacing the Strategic Arms Reduction Treaty with a new, legally-binding treaty.

The new START treaty, finally signed on April 8th, 2010, has reinforced the credibility of their commitment to a world without nuclear weapons[1]. This pledge is shared by a much wider constituency: on September 24th, 2009, on the initiative of the Obama administration, the UN Security Council held a summit meeting to "draw attention at the highest levels of government to the nuclear dangers confronting the international community and the urgency of taking concrete steps to address them". Fourteen heads of state and government unanimously adopted Resolution 1887 reaffirming the Security Council's commitment to a nuclear weapons free world and providing a framework for moving towards that goal[2].

Considering that nuclear weapons have dictated the international relations agenda for more than sixty years, even surviving the end of the cold war, this endeavour – and the term "nuclear weapons free world"– are truly revolutionary. Nuclear weapons are the most inhumane devices ever conceived, the only weapons that have the capacity to utterly destroy life on our planet; all the same, they are tacitly accepted by the public opinion worldwide, which seems to have forgotten their existence and consequent threats.

Scientists have devoted constant attention to the problem and appeals for the elimination of these weapons have been forwarded from time to time by prominent cultural or religious figures and peace movements; all the same, politicians have hastily dismissed them as a utopian dream. The 1968 Non-proliferation Treaty is the only legally binding document calling for nuclear disarmament; however, it does not specify concrete time schedules and procedures. In international relations, the phrase "complete nuclear disarmament" has been often used as a mere rhetorical artifice, undermining effective arms control negotiations. However, during the so-called Atomic Era occasions have arisen which have inspired serious thought to the matter and produced concrete initiatives worth considering for their relevance in the present time.

1.1. Early initiatives towards international control. Many of the scientists involved in the Manhattan Project believed that the international relations of their time could not cope with a weapon as destructive as the atomic bomb and advanced proposals for controlling atomic energy (Smith 1965).

As early as the latter part of 1943 the famous physicist Niels Bohr advocated international cooperation in dealing with nuclear weapons after the war in order to avoid an arms race between the Soviet Union and the Western powers. He saw the bomb as an opportunity as well as a danger, asserting that the very magnitude of the atomic threat made it necessary for states to cooperate, in a new approach to international relations based on openness and mutual trust (Bohr 1950). Bohr suggested that atomic energy be brought under international control, but he did not succeed in convincing either Roosevelt or Churchill (Aaserud 1999).

The idea of international control nevertheless remained on the political agenda. In January 1946 the United Nations established a commission to study how atomic weapons might be eliminated and atomic energy applied to peaceful uses. These objectives were also considered by a commission set up by the US State Department and chaired by Dean Acheson and David Lilienthal, with the key influence of Robert Oppenheimer, the scientist who directed the Manhattan Project. Oppenheimer was largely influenced by Bohr's ideas on the issue (Pascolini 2009) and was aware of the conclusions reached by the University of Chicago scientists on the subject of atomic energy, as expressed in the Franck Report (1945).

The Acheson-Lilienthal Report (1946) proposed that all dangerous activities be placed under an international Atomic Development Authority, while safe activities such as research and the peaceful uses of atomic energy were to be left under the control of individual states. The Atomic Development Authority would control world supplies of uranium and thorium, construct and operate plutonium production reactors and uranium isotope separation plants, and license the construction and operation of power reactors and other activities in individual countries (Pascolini 2009). This Report provided the basis for the US proposal presented to the UN Atomic Energy Commission in June 1946 by Bernard Baruch. Five days later, Andrei Gromyko presented a Soviet plan calling for a ban on the production, stockpiling, and use of atomic weapons, and for the destruction of all existing bombs within three months, without any provision for international control. Discussions continued in the Commission, but the prospects for an agreement dimmed as the two countries' relations deteriorated, and the effort to bring atomic energy under international control came to nothing.

1.2. The Reykjavik Meeting. The elimination of nuclear weapons, though often reiterated during the Cold War, was generally considered to be an unrealistic goal (Larking 2008). New hope for arms reduction came from the Reagan-Gorbachev unscheduled meeting in Reykjavik in October 1986. Gorbachev pushed for a set of daring proposals, including a 50% reduction in strategic nuclear forces and the elimination of medium- and intermediate- range missiles in Europe. In return he expected limitations on the Strategic Defence Initiative (SDI), Reagan's programme of research on missile defence. From the transcript of the discussions it becomes clear that at a certain point the two leaders were considering the possibility of a formal agreement for the total elimination of nuclear weapons within a 10-year span. The delegations accompanying Reagan and Gorbachev engaged in hard negotiation and made great progress towards agreements on both strategic and intermediate-range forces, but the SDI proved to be a stumbling block. Nevertheless, the negotiations at Reykjavik laid the basis for the 1987 INF (Intermediate Range Nuclear Forces) Treaty and the 1991 START I Treaty. The meeting was a major turning point in bringing the Cold War to an end and signalled the changing political relationship between the United States and the Soviet Union (Holloway 2010a).

1.3. The Hoover Initiative. In October 2006, the Hoover Institution at Stanford University[3] held a conference to mark the 20th anniversary of the Reykjavik meeting, with the objective of reconsidering the Reagan-Gorbachev vision of a world free of nuclear weapons. The primary organizers were George Shultz, Reagan's Secretary of State, and Sidney Drell, a Stanford physicist with a wide experience on national security issues and arms control. The most important result of the conference was an article by George Shultz, former Secretary of Defence William Perry, former Secretary of State Henry Kissinger and former Senator Sam Nunn in the *Wall Street Journal* in January 2007 (Shultz, Perry, Kissinger, Nunn 2007) calling for a world free of nuclear weapons.

The authors, with the active participation of Drell, started from the observation that the current situation is not likely to remain stable, being built on a discriminatory nuclear system with some countries possessing nuclear weapons and others denied the right to have them, and reached the conclusion that elimination of nuclear forces is both in the interest of common security and feasible. They suggested a number of steps to lay the basis for a world free of nuclear weapons: further reductions in nuclear forces; the de-alerting of U.S. and Russian strategic nuclear forces;

the elimination of short-range nuclear weapons; the ratification of the Comprehensive Test Ban Treaty[4]; and so on.

In October 2007 a second conference was held at the Hoover Institution to discuss the various steps that might be undertaken to move towards a world without nuclear weapons (Shultz, Perry, Kissinger, Nunn 2008).

The articles by the four statesmen elicited enormous interest in the United States, where both candidates to the Presidency endorsed them, and all over the world. Several governments have taken the Hoover Initiative seriously, including, as we have seen, the current Presidents of Russia and USA. One reason for the surprising impact of these articles is that they were written by political leaders who had a vast experience in national and international security policy and were not normally associated with utopian thinking; the second lies in the fact that the traditional nuclear deterrence strategies and the current approach to non-proliferation policy are generally viewed as inadequate.

Nuclear disarmament has now moved into the mainstream of international politics, becoming the focus of intense debate and discussion, with several institutions seriously studying approaches and possible concrete initiatives (Holloway 2010 b).

Charting a path to nuclear weapons elimination today is a more difficult challenge than it was in the 1940's, when only two countries had access to nuclear power, or in the early 1990's, at the end of Cold War. There are now nine nuclear-armed states, India, Pakistan and North Korea having joined USA, Russia, France, UK and Israel in the nuclear club, with diverging military and political interests; in addition, about 30 non-weapon states in NATO expect that nuclear weapons would be used in their defence if the need arises. In the transition to a nuclear-free world, some states will be concerned about the maintenance of the conventional military superiority of the great powers, and some will seek to preserve by other means their present status in the international system.

As stated by President Obama in his speech in Prague on April 5, 2009 (Obama 2009), "to seek the peace and security of a world without nuclear weapons, this goal will not be reached quickly – perhaps not in my lifetime. It will take patience and persistence".

Patience and persistence are required by the whole world community, according to individual capabilities, and scientists can help in solving the huge technical problems related to this ambitious objective.

2. Nuclear weapons and fissile materials. The total number of nuclear weapons has decreased in the last 20 years, but there are at least 23,000 nuclear warheads still in existence, with a blast capacity which adds up to more than 150,000 Hiroshima-scale explosions (SIPRI 2010). Nearly half of all these weapons are operationally deployed, and over 2,000 of them remain on dangerous high alert status, ready to be launched on warning within four to eight minutes.

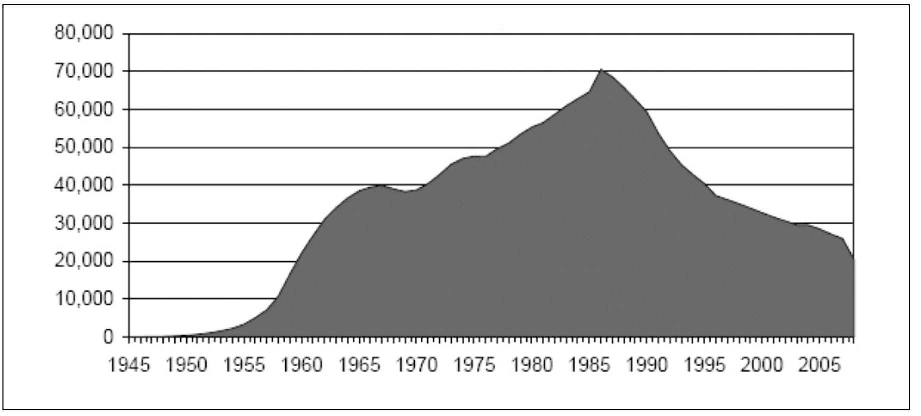

Figure 1. Evolution of global nuclear stockpiles 1945-2008[5].

As Figure 1 suggests, Reykjavik was indeed a turning point in the US-Soviet nuclear arms race: 1986 was the year in which the number of nuclear weapons peaked, and the Reykjavik summit marks the starting point if a process of nuclear arms reductions that has continued to this day.

The huge number of nuclear warheads and of their delivery vehicles is only the tip of the iceberg of the complex military-scientific-industrial-bureaucratic environment devoted to the research, development, production and deployment of nuclear forces, which also includes specific systems of communication, intelligence and control, simulations, the special training of soldiers and the constant upgrading of military strategies. A truly "nuclear weapon free world" requires the total dissolution of these multi-faceted apparatuses which have developed around the military nuclear postures. For this to happen a strong political commitment is necessary, together with the complete cooperation from the military leadership and the relevant bureaucratic institutions of nuclear weapon states.

The elimination of the existing weapons is only one side of the problem: the conditions must be created to prevent any country – and any subnational group or terroristic organization – from acquiring the capability of producing new nuclear devices. The problem is made more complex by the very existence of the civilian nuclear energy programmes, which are presently considered an important economic asset by most countries, and which require a guaranteed access to nuclear fuel. As a result, a system of safeguarded international arrangements needs to be created to prevent states from breaking out of the non-nuclear regime.

Therefore, a global commitment is indispensable in order to reach solutions to the scientific and technical difficulties posed by this new challenge. To appreciate the technical problems a few basic facts about nuclear weapons must be understood[6]. Present nuclear weapons are very sophisticated technological devices, designed to perform in a prefixed way, with a selected mix of effects, but basically they are either fission or fission-fusion thermonuclear devices.

2.1. Nuclear weapons. The nuclear fission reaction consists in the splitting, induced by a neutron, of the atomic nucleus of isotopes of uranium (U) or plutonium (Pu) in two smaller nuclei with the release of new neutrons and large quantities of energy. The emitted neutrons can induce further fissions in a chain reaction, which, in special conditions (critical or supercritical), can proceed involving more and more fissile material, in a slow and controlled way in nuclear reactors and in a quick and explosive manner in atomic bombs. In a typical weapon, some kilograms of fissile material fission in less than a microsecond and produce an energy equivalent to the explosion of tens of thousands of tonnes of high explosives[7]. Part of this energy originates a blast wave, part is diffused as light and thermal radiation, part is carried by an intense flux of neutrons, gamma- and X-rays. All these factors contribute to the destructive effects of nuclear explosions.

A minimum amount of material is needed for sustaining a chain reaction, in order to avoid that too large a fraction of the neutrons escape from the surface rather than being absorbed by fissile nuclei. The amount of material required to constitute a

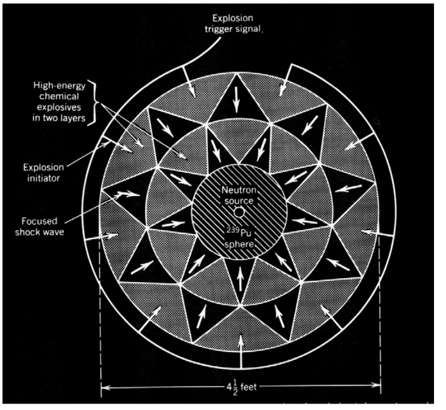

Figure 2. Schematic representation of the implosion mechanism for a fission weapon (Schroeer 1984).

"critical" mass vary widely – depending on the fissile material, its chemical form, and the properties of the surrounding materials that can reflect neutrons back into the core. The significant quantities are 8 kg for plutonium and 25 kg of U-235. The United States has declassified the fact that with proper reflectors/tampers the critical masses reduce to 15 kg of pure U-235 and 4 kg of Pu-239[8].

A weapon design requires a sudden reconfiguration of the fissile material from a safe subcritical condition to a supercritical explosive one: in the current method the core of a subcritical mass of uranium or plutonium is compressed beyond its normal metallic density to a high supercritical density, by means of a series of chemical explosions, which produce in a few microseconds a convergent shock wave (implosion).

The nuclear fusion reaction consists in the merging of two smaller nuclei in a bigger one, a process which gives energy to the stars and is responsible for the production of heavier elements from initial hydrogen. This reaction is sustained by nuclear forces, but hindered by the electric repulsion between nuclei, and only happens in special conditions of high density and extreme temperatures – millions of degrees. The fusion of hydrogen heavy isotopes deuterium and tritium in helium with the release of neutrons requires temperatures of more than 100 million degrees, but produces a large amount of energy: its energy density for unit mass is 4 times that of the fission of uranium and 40 million that of the TNT explosion.

In modern nuclear weapons, the yield of the fission explosion is enhanced ("boosted") by a factor of ten by introducing a mixed gas of deuterium and tritium into a hollow shell of fissile material just before it is imploded. When the temperature of the fissioning material reaches about 100 million degrees, it ignites the fusion of tritium with deuterium, which produces a burst of neutrons that increases the fraction of fissile materials fissioned and thereby the power of the explosion.

In a fission-fusion weapon, the explosion of a fission "primary stage" generates X-rays that are driven in a foam to compress and ignite a "secondary stage" containing thermonuclear fuel of lithium-6 deuteride, where much of the energy is created by the fusion of deuterium and tritium. The tritium in the secondary stage is made during the explosion itself by neutrons splitting lithium-6 into tritium and helium.

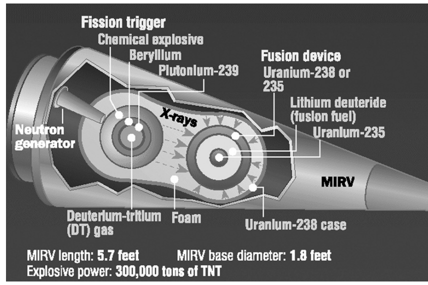

Figure 3. Schematic design of a modern thermonuclear nuclear warhead (Cox 2009).

It should be noted that a fusion weapon is only possible if triggered by a fission explosion, to provide for the high temperature and the flux of compressing X-rays. While there is a limitation to the maximum energy achievable by a boosted fission weapon, in the range of few hundreds kilotons, no limit exists for thermonuclear devices, the biggest device of such kind, the soviet "Czar Bomb", having released the energy of 50 megatons.

A nuclear weapon is a complex mechanism, requiring, in addition to the nuclear explosive, arming, fusing, firing and safety systems. Therefore the production of nuclear weapons necessarily requires:
– expertise in the field of nuclear science,
– mastering several non-nuclear technologies,
– ability in the techniques of high explosives,
– fissile materials of explosive quality.

2.2. Fissile materials. Scientific competence and technological expertise

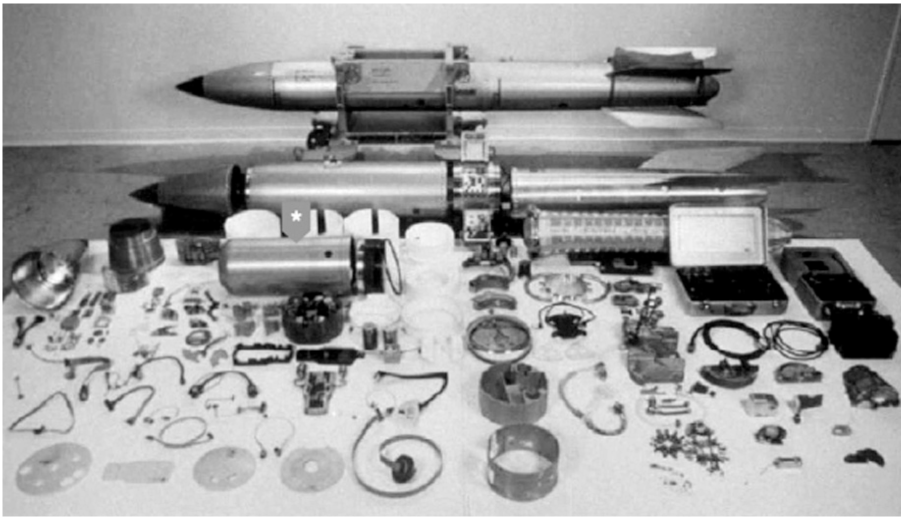

Figure 4. Components of a U.S. B-61 thermonuclear gravity weapon for aircrafts. The nuclear explosive is indicated with (*) (Source: U.S. Department of Energy).

cannot be controlled or prohibited; what makes nuclear disarmament a feasible proposition is the fact that fissile materials for military use are not easily obtainable and require extremely complex methods and large facilities for their production. In fact plutonium does not exist in nature and the fissile U-235 isotope only occurs in the fraction of 0.72% of natural uranium, the remaining part being (practically) non-fissile U-238.

Enriched uranium. The fissile U-235 isotope can be found in:
– depleted uranium, with less than 0.3% U-235;
– natural uranium, with 0.72% U-235;
– reactor-grade uranium, with 4 to 5% U-235;
– low-enriched uranium (LEU), with less than 20% U-235;
– highly enriched uranium (HEU), with over than 20% U-235;
– weapon-grade uranium (WGU), with over than 90% U-235.

Although an infinite mass of uranium with a U-235 enrichment of 6% could, in principle, sustain an explosive chain reaction, according to weapons experts, HEU is required to make a fission weapon of practical size. Current nuclear weapons only use WGU.

The process of uranium enrichment in the component of U-235 is extremely complex and requires a sophisticated isotope separation technology, large industrial plants and enormous quantities of energy. The isotopes U-235 and U-238 are in fact virtually identical in their chemical structure and differ in weight by only 1%. In a uranium facility, the process

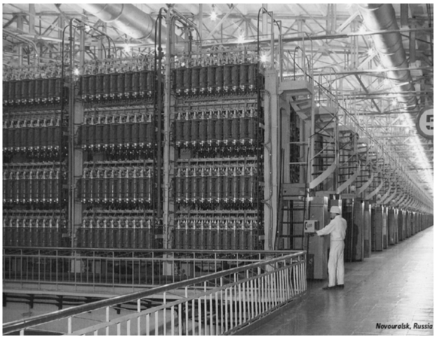

Figure 5. Inside the Russian Novoulask centrifuge enrichment plant; Russian centrifuges are short and stacked on top of each other (Source: Russian Ministry of Atomic Energy).

of enrichment splits the natural uranium into two streams: a product stream enriched in U-235, and a waste stream depleted in U-235. Today, the largely dominant enrichment technology on a commercial scale is based on centrifuges[9]. Gas centrifuges spin uranium hexafluoride gas at enormous speeds, so that the uranium is pressed against the wall with more than 100,000 times the force of gravity. The molecules containing the heavier U-238 atoms concentrate slightly more towards the wall than the molecules containing the lighter U-235, allowing the physical separation of the two isotopes. An enrichment plant consists of several thousands of centrifuges, connected in a cascade of several stages.

Enrichment plants are necessary for the production of LEU, used by the large majority of nuclear power plants, but at the same time they are crucial for acquiring HEU and WGU for weapons. The same plant, starting from 150 t of natural uranium, can produce in a year's time either 20 t of 4% LEU to feed one 1GWe power plant, or 550 kg of 93% HEU, sufficient for 26 weapons. In the first case the centrifuges are arranged in 10 stages, in the second in 32 stages.

Enrichment capabilities on a scale sufficient to make nuclear weapons or enough LEU fuel to sustain a large power reactor exist in a relatively small number of nations. Currently, there are ten states where civilian uranium enrichment plants are either fully operative, under construction or planned: Brazil, China, France, Germany, Iran, Japan, the Netherlands, Russia, the United Kingdom, the United States. These enrichment plants are designed to produce LEU for nuclear power reactor fuel, but could in principle be quickly converted into producing HEU for weapons. India is militarily producing HEU for naval propulsion, and Pakistan remains the only country enriching uranium for weapon production.

Plutonium. Plutonium is an artificial isotope produced in nuclear reactors when U-238 absorbs a neutron creating U-239, which subsequently decays to Pu-239 via the intermediate short-lived isotope neptunium-239.

In order to be used in a nuclear weapon, plutonium must be separated from the spent fuel of the reactor, which also contains highly radioactive fission products. With the current PUREX "reprocessing" technology, the spent fuel is chopped into small pieces and dissolved in hot ni-

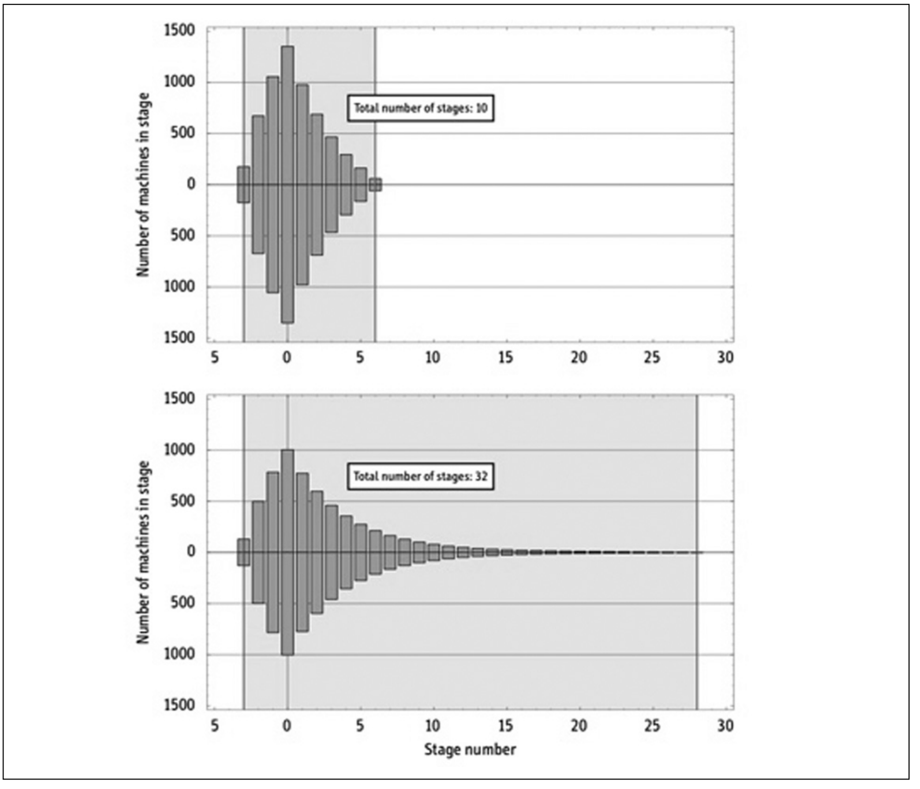

Figure 6. Two alternative arrangements of the same number of centrifuges, to produce LEU or military HEU (IPFM 2006).

tric acid; plutonium is then extracted in an organic solvent that is mixed with the nitric acid using blenders and pulse columns, and finally separated with centrifuge extractors. Owing to the very intense radiation field of the material, every phase of the procedure requires heavy shielding and remote handling. The literature regarding the technical details of plutonium reprocessing is easily accessible to the public, but special resources and technical expertise are necessary. Separated plutonium is only slightly radioactive and can be handled and worked without radiation shielding, but is dangerous when inhaled or ingested.

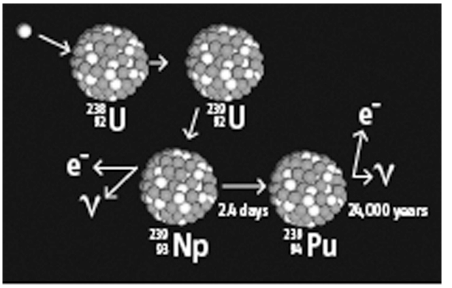

Figure 7. Reactions in a nuclear reactor transforming uranium in plutonium.

The longer an atom of Pu-239 is kept in a reactor after its creation, the greater the likelihood that it will absorb a second neutron and fission or become Pu-240, or absorb a third or fourth neutron and become Pu-241 or Pu-242. Plutonium therefore comes in a variety of isotopic mixtures. Plutonium in typical power-reactor spent fuel (reactor-grade plutonium RPu) contains 50-60% Pu-239, and about 25% Pu-240. Weapon designers prefer to work with a mixture that is as rich in Pu-239 as possible, because of its relatively low rate of generation of radioactive heat and relatively low spontaneous emissions of neutrons and gamma rays, which can cause a "pre-detonation" reducing the yield a thousand-fold. Weapon-grade plutonium (WPu) contains more than 90% of the isotope Pu-239 and has a critical mass about three-quarters that of reactor grade plutonium. Modern weapon designs are insensitive to the isotopic mix in plutonium, and a U.S. Department of Energy report (1997) states:

> Virtually any combination of plutonium isotopes [...] can be used to make a nuclear weapon [...] reactor-grade plutonium is weapons-usable, whether by unsophisticated proliferators or by advanced nuclear weapon states.

This fact makes the reprocessing technology critical, in view of nuclear disarmament and non-proliferation strategies. The major problem lies in the interest of civilian nuclear industry in recovering plutonium from spent fuel to produce new fuel in the form of "mixed oxides" (MOX) to be used in nuclear reactors. MOX fuels are nuclear reactor fuels composed of a mixture of plutonium (about 4%) and natural or depleted uranium in oxide form, plutonium replacing the U-235 in LEU as the primary fissioning material. MOX fuels are much more hazardous and expensive to fabricate than standard uranium. Also, handling a weapon-usable material like plutonium requires much more stringent safeguards and security than are required at a facility fabricating LEU-fuel. Today, China, France, Japan, Russia, and the United Kingdom operate reprocessing plants for commercial purposes, while in the United States a small facility is used for extraction of HEU. India, Israel, North Korea and Pakistan continue to produce plutonium for weapons.

3. Challenges. As nuclear armaments have dominated the global scenario for so many years, a world "free of nuclear weapons" can be hard to envision. As Holloway (2010b) points out:

> What would it really mean to be "free of nuclear weapons?" Would there be many states with the capacity to produce nuclear weapons in a short time? Would a nuclear-weapons-free world require new kinds of intrusive inspection? Are the necessary means of verification available? Would there always be the danger of breakout? What could be done to mitigate that danger? What will the end state look like?

These are extremely important questions, which have begun to receive the attention they deserve (Drell and Goodby 2009, Evans and

Kawaguchi 2009), but equally important is the question of how to overcome the obstacles to a world free of nuclear weapons and ensure its security and stability. These challenges include the mechanism shaping the disarmament progress, the issue of reversibility, the management and elimination of fissile material stocks, and the risks of nuclear weapon reconstitution or proliferation using material and capabilities in civilian nuclear energy programmes. In the transition to zero a considerable degree of reversibility would be inevitable, because of the stockpiles of fissile material from the dismantled weapons and the engineering experts in weapons design. The countries will also retain production plants and production and maintenance facilities, all of which will require monitoring until they are decommissioned or converted to civilian purposes.

If nuclear weapons are to be eliminated, plutonium and HEU will have to be eliminated from their cores. Also, stocks of these materials produced to fuel nuclear reactors or for other purposes, but which could be used to make nuclear weapons, will have to be minimized and the remainder heavily safeguarded.

All nuclear power plants produce spent fuel containing plutonium as part of their normal operation and the already-separated civilian plutonium is enough to produce at least 30,000 nuclear warheads.

Securing the eventual elimination of nuclear weapons will require that the international community develop a strategy and be prepared to respond to non-compliance immediately and effectively. The desirable and indeed essential characteristics to an effective system of safeguards were considered at the very beginning of the atomic era by the scientists who had worked on the Manhattan Project (Federation of American Scientists 1946). A list of these characteristics was authoritatively drawn up in the Acheson-Lilienthal Report, which still today remains the fundamental criteria for adequate security plans.

> a. Such a plan must reduce to manageable proportions the problem of enforcement of an international policy against atomic warfare.
> b. It must be a plan that provides unambiguous and reliable danger signals if a nation takes steps that do or may indicate the beginning of atomic warfare.
> c. The plan must be one that if carried out will provide security; but such that if it fails or the international situation collapses, any nation will still be in a relatively secure position.
> d. To be genuinely effective for security, the plan must be one that is not wholly negative, suppressive, and police-like. Therefore the plan must be one that will tend to develop the beneficial possibilities of atomic energy and encourage the growth of fundamental knowledge, stirring the constructive and imaginative impulses of men rather than merely concentrating on the defensive and negative.
> e. The plan must be able to cope with new dangers that may appear in the further development of this relatively new field. In an organizational sense therefore the plan must have flexibility and be readily capable of extension or contraction.
> f. The plan must involve international

> action and minimize rivalry between nations in the dangerous aspects of atomic development.
> We are not dealing simply with a military or scientific problem but with a problem in statecraft and the ways of the human spirit.

In conclusion, the basic principle behind the proposal was to prohibit nations from developing their own nuclear energy structure and put the crucial part of nuclear development under the supervision of an international agency.

Over the years a great deal of experience has been accumulated in exercising national and international control over nuclear materials and technology. Fissile material accountancy and monitoring lie at the heart of the system of International Atomic Energy Agency's safeguards, required by the Non Proliferation Treaty so as to verify that non-weapon states abide by their commitments not to divert fissile material to nuclear-weapon production. But much more is required to extend the control to nuclear-weapon states and a lot of research is necessary (Johnson 2009).

One option to reconsider, following the Acheson-Lilienthal report, might be to place all nuclear material under international ownership and make national appropriation of nuclear material an offence under international law (Committee on the Internationalization of the Civilian Nuclear Fuel Cycle 2008).

4. Elimination of HEU. The nuclear confrontation during the Cold War produced over 2500 t of HEU, mostly weapon grade, sufficient for some 100,000 warheads; they were used for the construction of weapons and, for a large fraction, for naval propulsion. The USA and the Soviet Union accounted for over 95% of the global HEU production: 1045 t of HEU

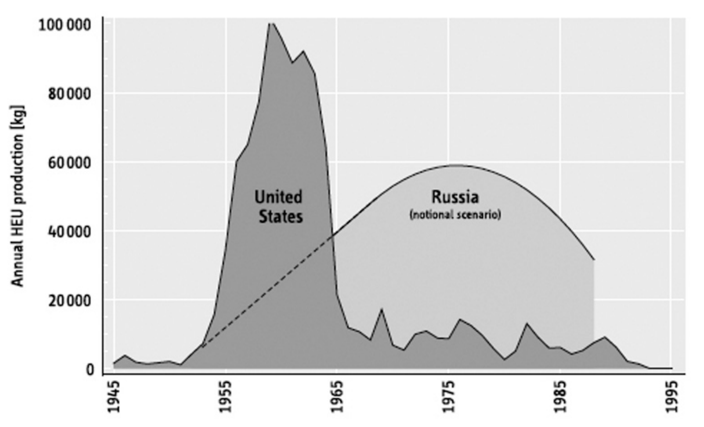

Figure 8. Historical production rates of HEU in the United States and Russia (IPFM 2008).

Table 1. National stocks of HEU in tonnes as of mid-2009 (IPFM 2009).

Country	Weapons	Naval	Civilian	Excess
China	20 ± 4			
France	30 ± 6		5.1	
India	0.6 ± 0.3			
Israel	0.1			
Pakistan	2 ± 0.4			
Russia	590 ± 144	150 ± 30	30 ± 6	133
UK	17.4	4.5	1.4	
USA	250	228	30	109
Other			10	
Total	910.1 ± 154.7	382.5 ± 30	76.5 ± 6	242

with an average enrichment of 82% were produced by the USA and approximately 1400-1500 t (90% enriched) were fabricated by Russia[10]. As plotted in Figure 8, annual US production peaked in 1959 at 102,000 kg of HEU, while Russia peaked at around 60,000 kg/yr in the mid-1970's.

Table 1 shows the mid-2009 global stockpile of HEU, still reaching about 1600 ± 300 t, enough for more than 60,000 nuclear weapons. Prior to this, Russia had eliminated 367 t of HEU and the USA 124 t. The large uncertainty is due to the fact Russia did not declare how much HEU it had produced before it ended production in the late 1980's.

4.1. HEU disposal. The disposal of HEU is relatively easy because it can be converted to low-enriched uranium containing 4-5% U-235 by dilution with depleted, natural or slightly enriched uranium. LEU cannot sustain an explosive nuclear chain reaction but is used to fuel most of the world's nuclear-power reactors and is therefore of commercial value. The process of elimination of uranium weapons begins with the conversion of HEU weapon components into metal shavings, which are then converted into oxide. The oxide is put through a solvent extraction process to remove chemical impurities and then transformed into UF_6 gas, which is blended with a stream of UF_6 gas enriched to 1.5-% U-235. The 1.5-% enriched blend-stock is made by stripping more U-235 out of already depleted "tails" from past enrichment operations. About 30 tons of this blend-stock are required to dilute one ton of HEU, and the produced LEU is sufficient to fuel a typical one-gigawatt reactor for 1.5 years.

Currently, the USA is purchasing LEU from 30 t of blended-down Russian weapon-grade HEU, resulting in about 900 t of LEU per year, enough to provide the annual fuel requirements for 45 GWe of light-water reactor capacity. This is equivalent to about 45% of the U.S. nuclear capacity or 12% of global capacity. The U.S.-Russian blend-down contract re-

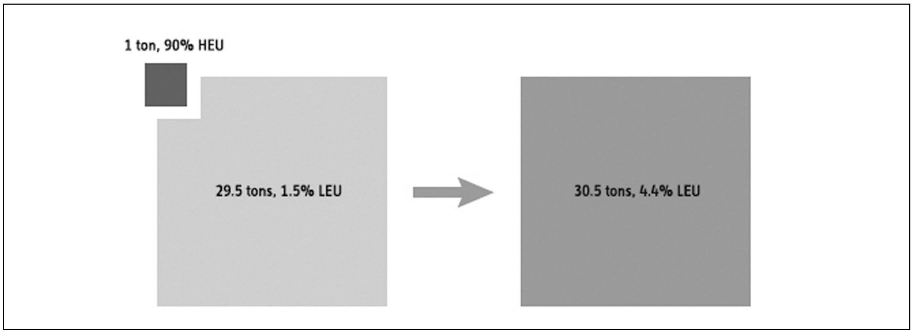

Figure 9. Schematic showing of the blending process of one ton of 90% enriched uranium to LEU.

garding 500 t of HEU, the equivalent of 20,000 warheads, is scheduled to be completed by the end of 2013 (Pascolini 2008).

Blend-down to LEU is the main approach that is being pursued for disposing of un-irradiated HEU. For HEU in spent fuel from naval propulsion and research reactors, two approaches are being pursued:

– reprocessing to recover the HEU, which is then blended down to LEU;
– direct disposal in a geological repository alongside power-reactor spent fuel.

Reprocessing is costly and alternatives are being explored, both to reduce costs and generate less waste.

4.2. Non-weapon use of HEU. In the perspective of a nuclear weapon free world, all HEU should be eliminated, finding alternative solutions for its current use. The present most important non-weapon uses of HEU are limited to:

– production of fuel for naval reactors;
– production of fuel for Russian fast reactors;
– production of fuel for research reactors;
– manufacturing of targets for production of radio-pharmaceutical isotopes.

Naval propulsion reactors. HEU has been especially attractive for naval propulsion reactors, for submarines and military surface vessels in particular, because of the need for compact cores (that is, cores with large burn-up potential using minimum space). HEU-fuelled naval propulsion installations in operation today include 193 reactors in four nuclear weapon states. In addition to submarines, USA has nuclear propelled aircraft carriers and destroyers and Russia cruisers and an icebreaker fleet. The total HEU consumption of naval vessels worldwide in 2007 was 3,140 kg (± 50%), about 2/3 used by American ships.

The HEU fuel in the fuel cycle of these reactors has been a major proliferation concern. France is shifting

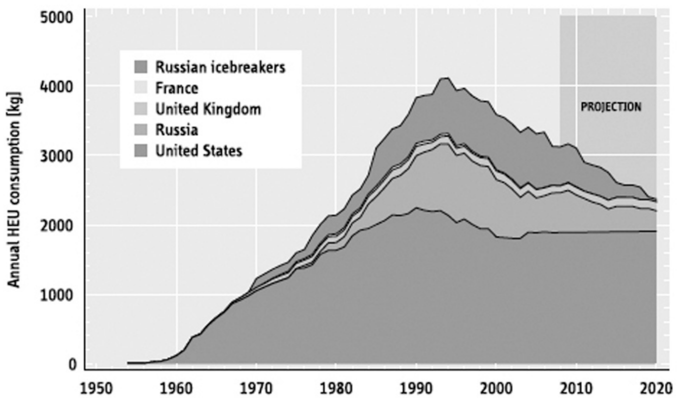

Figure 10. HEU consumption for naval propulsion (IPMF 2009).

its naval-propulsion reactors from HEU to LEU fuel for economic reasons. In Russia studies are being pursued to develop LEU fuel for the icebreaker reactors, which could prove useful for the other naval vessels. Converting U.S. and U.K. naval reactors to LEU would be more difficult. French and Russian reactors are refuelled every 5 to 10 years. The U.S. and U.K., in an effort to avoid refuelling shutdowns, are moving to reactor cores designed to last the lifetime of the ship – up to 45 years (Ma and von Hippel 2001). For this reason the USA is reserving the largest stocks of its HEU for naval propulsion.

Research reactors. Nuclear research and test reactors have been in operation for more than 60 years, their primary purpose being to provide a neutron source for a wide range of uses. They underpin the development of power and propulsion reactors and are major research tools in the fields of nuclear physics and engineering, nuclear chemistry, materials science, and biology, and they contribute to scientific and technological advances in medicine, industry, and agriculture. Research reactors have become indispensable for the production of medical isotopes to supply a rapidly increasing demand for diagnostic and therapeutic procedures based on nuclear medicine techniques. More than 700 research reactors have been commissioned worldwide, and 240 of these are currently in operation in 55 countries; another 9 reactors are in various stages of construction and several more are planned.

They are smaller and simpler than power reactors and operate at lower temperatures. They need far less fuel, but, on the other hand, their fuel requires more highly enriched uranium, typically up to 20% U-235, although some ones use 93% U-235. The total

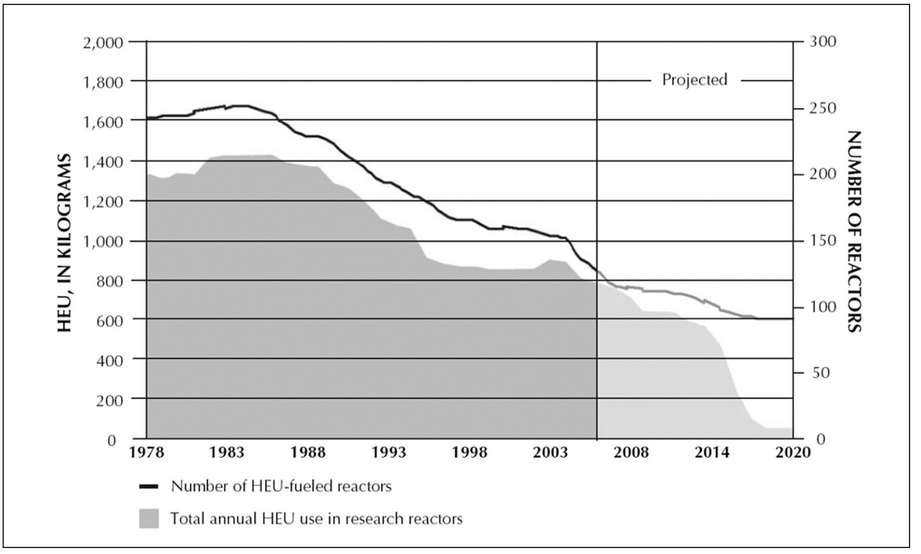

Figure 11. Annual HEU use in research reactors and the number of HEU-fuelled reactors, 1978-2020 (Reistad and Hustveit 2008).

consumption of the eighteen largest HEU-fuelled research reactors has been calculated to be 598 kg in 2007, 76% of the total HEU consumption (787 kg) worldwide (Reistad and Hustveit 2008). The question of enrichment was a major focus of the UN-sponsored International Nuclear Fuel Cycle Evaluation in 1980. It concluded that to guard against weapons proliferation, enrichment should be reduced to no more than 20% U-235. This followed a similar initiative by the USA in 1978 when its programme for Reduced Enrichment for Research and Test Reactors was launched. The risks of proliferation and of terrorist theft are due in particular to the dispersion of these reactors and their often inadequate security protection (von Hippel 2004). Overall 129 reactors out of the 207 using HEU in 2007 are targeted for conversion, and some 20 t of HEU is involved. To September 2009, 67 research reactors had been converted to low-enriched uranium silicide fuel or shut down and another 34 are convertible using present fuels. A further 28 need higher-density fuels not yet available. The goal is to convert or shut 129 reactors by 2018.

The variety of types of research reactors requires individual studies of each plant in order to convert it without incurring a significant technical penalty in performance. An international effort is underway to develop, qualify and license a high density fuel based on uranium-molybdenum alloy dispersed in aluminium, in order to provide fuels which can extend the use of LEU to those reactors requiring higher densities than available in silicide dispersions and that can be more easily reprocessed (Bradley, Adelfang, Goldman 2007). The most prominent and difficult case is the research reactor FRM-II near Munich, Germany, which went into operation in 2004 and requires 35-40 kg of weapon-grade HEU per year. Studies for an enrichment reduction to 50% or less are currently underway.

Medical isotope production. Targets of weapon-grade uranium placed in high neutron fluxes near the cores of high-powered research reactors are the principal sources for a number of short-lived fission products that have become important to modern medicine, primarily technetium-99m (Tc-99m), iodine-131 and xenon-133. Approximately over 50 kg of HEU are used annually for medical isotope production. Tc-99m is used in approximately 80-85% of the world's diagnostic imaging procedures (cardiac perfusion scans and bone scans among them), about 20 million procedures yearly. Tc-99m has a 6 hour half-life and emits a gamma ray when it de-excites. Attached to various chemicals, it can be followed by its gamma emissions through the body and thereby can be used to examine the functioning of various organs. Its short half-life and lack of beta radiation minimizes unnecessary radiation doses. It is derived via radioactive decay (half-life of 2.7 days) from molybdenum-99 (Mo-99), produced by the fission of uranium[11]. Mo-99 is absorbed onto the surface of a bed of small alumina particles in "generators" from which the technetium is drawn off in solution.

In the production of molybdenum from weapon-grade enriched uranium, less than 5% of the targets are consumed and the rest is stockpiled as waste; while the isotope producers provide security for HEU transport and storage, it is unclear whether the security is stringent enough to eliminate the risk of theft. In the perspective of HEU elimination several studies are underway to identify alternative techniques to produce molybdenum (von Hippel and Kahn 2006).

The challenge is to identify those techniques which have high yields and high specific activity, and are economically competitive with the present production method. Using particle beams, three different processes are possible (Fong, Meyer, Zala 2008):

– the neutron-capture process: an intense neutron beam generated by a nuclear reactor adds one neutron to a Mo-98 target to produce Mo-99;
– the photo-neutron process: an intense photon beam generated by an electron accelerator removes a neutron from a Mo-100 target to produce Mo-99;
– the photo-fission process: a very intense photon beam generated by an electron accelerator causes a uranium target to fission to produce Mo-99.

To make use of these alternative approaches a number of technical challenges must be overcome not the least of which is the availability of the desired Tc-99m in a useful chemical form and of the same quality as the fission product for use with the many

TABLE D.1 Comparison of Fission and Neutron Produced ^{99}Mo

$^{235}U(n,f)^{99}Mo$	$^{98}Mo(n,\gamma)^{99}Mo$
Produces high specific activity ^{99}Mo	Produces low specific activity Mo-99
Requires enriched ^{235}U target	Requires highly enriched Mo-98 target
Complex chemical processing	Simple chemical processing
Requires dedicated processing facility	Requires high flux neutron source
Generates high-level radioactive waste	Generates minimal waste

Figure 12. Comparison of the two main methods for production of Mo-99 (Committee on Medical Isotope Production without Highly Enriched Uranium 2009).

radiopharmaceutical kits now on the market.

The most commonly used of these alternative methods involves the neutron capture on an enriched target of Mo-98 (natural occurrence of Mo-98 is 24.13%), and Figure 12 compares the two main methods.

Another point to consider, although of secondary importance, is the fact that several other radionuclides of medical importance are coproduced in the fission process and would require an alternative source in the case of a neutron capture process.

A recent study by the American National Academy of Sciences (Committee on Medical Isotope Production without Highly Enriched Uranium 2009) strongly suggests replacing HEU targets with LEU ones as the best alternative method. This approach has been already operating in Argentina since 2002. An Argentine-designed and -built reactor near Sydney, Australia, will produce Mo-99 with LEU fuel and targets in the near future, and an Argentine company is completing construction of a Mo-99 processing facility at an all-LEU reactor near Cairo, Egypt. Further research is necessary to improve this method, in particular for an efficient radiochemical Mo-99 extraction, in order to assure the necessary quality of the product, reduce radioactive waste and control plutonium production.

5. Elimination of plutonium. The global stockpile of separated plutonium is over 570 t, with civilian stocks larger than military ones – the latter including material declared excess but not yet disposed. A one-GWe light water reactor (LWR), operating at a 90% capacity, produces about 250 kg of plutonium per year. The total spent fuel generated annually by power reactors is approximately 10,000 t, containing about 75 t of plutonium. Roughly one fourth of the spent fuel generated each year is reprocessed; most of the remainder is being stored at reactor sites.

Unlike HEU, weapon-grade plutonium cannot simply be eliminated as a potential weapon material by dilution with a non-fissile isotope. All plutonium isotopes but Pu-238, which is available in only relatively

Table 2. National stocks of separated plutonium in tonnes as of mid-2009 (IPFM 2009).

Country	Military	Additional strategic	Civilian in the country	Civilian stored outside	Excess military
Belgium				1.4	
China	4 ± 0.8				
France	5 ± 1		54.9		
Germany			1	12	
India	0.7 ± 0.14	6.8 ± 1.36			
Israel	0.65 ± 0.13				
Japan			87	38	
North Korea	0.035 ± 0.018				
Pakistan	0.1 ± 0.02				
Russia	111 ± 25		44.9		34
UK	3.5		76.8	0.9	4.4
USA	38				53.9
Total	163 ± 27	6.8 ± 1.36	264.6	53.3	92.3

small quantities, can support an explosive chain reaction. This makes plutonium disposal perhaps the most difficult problem for a permanent freedom from nuclear weapons.

Extensive studies from the U.S. National Academy of Sciences (Committee on International Security and Arms Control, 1994 and 1995) and from an US-Russia scientific commission (Holdren and Velikhov 1997) laid out potential plutonium-disposition options. One option would be to store excess inventories of separated plutonium indefinitely in high-security facilities, under the vigilance of the responsible institutions: however, it would remain available for remanufacture into nuclear weapons quickly and at low cost.

Beyond storage, the two least problematic approaches would be: mixing the plutonium with uranium, fabricating it into mixed oxide (MOX) fuel and irradiating the material in existing reactors, or immobilizing the plutonium with high-level wastes. Both of these approaches would result in most of the plutonium being embedded in large, intensely radioactive waste forms from which it would be difficult and costly to recover.

Disposition begins with plutonium being separated from other materials and converted to an oxide. In the MOX fuel approach, plutonium oxide would be mixed with uranium oxide, pressed, baked and ground into cylindrical ceramic pellets, and loaded into long metal tubes to make fuel rods. After irradiation in a reactor, the spent MOX fuel would still contain about two thirds as much plutonium, but in large, intensely radioactive fuel assemblies that would require remotely-handled chemical processing to recover the plutonium.

The MOX approach is a slow one for disposing plutonium: for safety

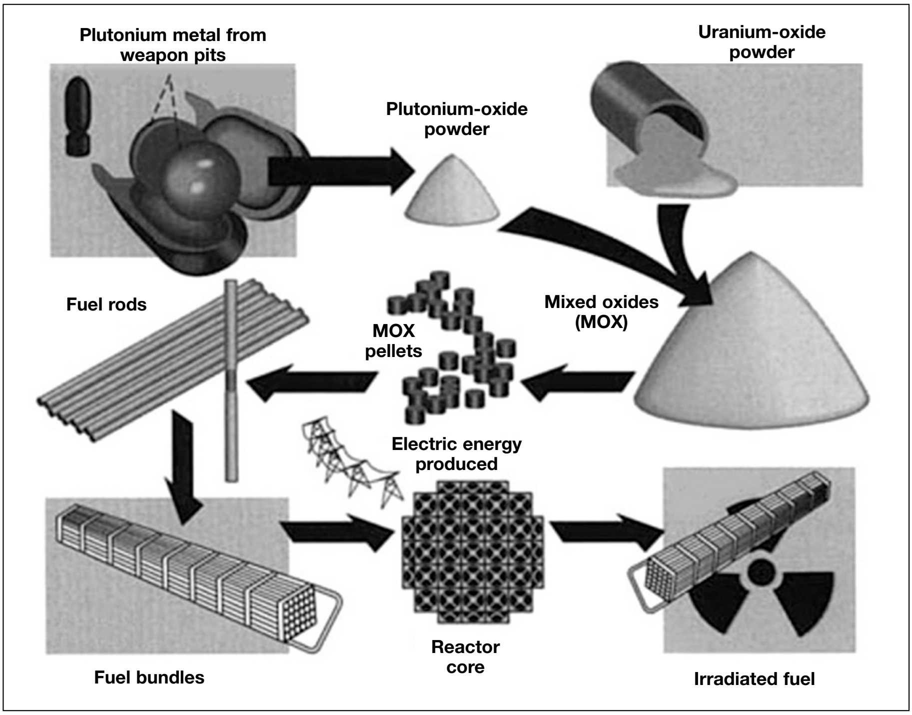

Figure 13. Diagram of disposition of plutonium from weapons as MOX fuel (Pascolini 2008).

reasons, LWRs are limited to using MOX for only one-third of their cores, which reduces the amount of plutonium loaded per GWe-year to about 300 kg. Fast-neutron reactors designed for full MOX cores can use fuel with much higher plutonium concentrations. Russia's demonstration 0.8 GWe BN-800 fast-neutron reactor, currently under construction, is expected to be able to irradiate some 1.6 tons of plutonium in MOX each year.

In the immobilization approach, the plutonium would be immobilized in either a glass or a ceramic form. Mixing plutonium and high-level waste to form a homogeneous glass or ceramic poses challenges ranging from the need to avoid criticality to the difficulty of finding waste forms and production processes that can handle substantial concentrations of both plutonium and fission products. Alternative approaches are under study (IPFM 2007).

Russia's nuclear-energy establishment has always seen its excess plutonium as an asset that should be used to produce energy, and cannot accept to immobilize it. In the year 2000, Russia and the United States agreed to eliminate 34 tons of weapon plutonium each with an additional 4 t of reactor grade plutonium. Under the earlier version of the plan, Russia would have turned plutonium into MOX for use in Russian LWRs. That effort stalled over programmatic, financial, and legal differences. On April 13, 2010 the two countries signed a protocol to the 2000 agreement, allowing the use of MOX in Russian fast-neutron reactors (Horner 2010); actual disposal in both countries should start by 2018.

6. Conclusion. The elimination of nuclear weapons worldwide has long been a goal pursued by different pressure groups, each having different reasons and motivations. Scientists have been the first to perceive the potential threats of these new indiscriminate weapons and a large part of them acted for nuclear disarmament and cooperated in the various international initiatives for curbing the arms race and for arms control. Presently, political leaders are adopting the idea that a world without nuclear weapons is feasible, realistic and in the common interest, stimulating public attention and studies on this theme. This creates new opportunities for political action at national and international levels worldwide, which need to be brought to the attention of the general public and supported by non-governmental organizations interested in peace and human security.

The enormous scientific and technological difficulties associated with the transition from the present situation to a world without nuclear weapons, only a part of which has been considered in this paper, call for intensive research by a vast array of scientists in numerous fields of discipline. These problems are scientifically more challenging than the development of weapons, field to which a considerable part of the scientific community has dedicated itself up until today, and can provide new interesting subjects of research and work opportunities to the scientists and technicians presently employed in the production and management of these weapons (Reppy 2010). In such an enterprise, as the Acheson-Lilienthal report reminds us, “we are not dealing simply with a military or scientific problem but with a problem in statecraft and the ways of the human spirit”.

[1] The texts of the *Treaty between the United States of America and the Russian Federation on measures for further reduction and limitation of strategic offensive arms*, vulgo “New START”, of its protocol and of three annexes can be found at the site of U.S. Department of State. The new treaty is important for political reasons, restarting positive relations between Russia and USA and providing a framework for further reductions in strategic nuclear forces, but foresees only timid reductions of a class of nuclear weapons and of their delivery vehicles (Pascolini 2010).

[2] The text of the resolution can be found at the UN website.

[3] The Hoover Institution is a conservative research institute often associated with the U.S. Republican Party.

[4] The Comprehensive Nuclear Test-Ban Treaty

(CTBT), opened for signature at New York on 24 September 1996 and not in force as of 10 June 2010, prohibits the carrying out of any nuclear weapon test explosion or any other nuclear explosion. A global verification regime comprises a global network of monitoring stations, an International Data Centre in Vienna, a consultation and clarification process, on-site inspections, and confidence-building measures. As of June 10, 2010, there are 182 member states, 153 ratifications have been deposited, but 9 of the 44 states necessary for entering in force are still missing (China, Egypt, India, Indonesia, Iran, Israel, North Korea, Pakistan and USA). The text of the treaty can be found at the UN website.

[5] Figure 1 is based on the estimates of nuclear stockpiles by Norris, Kristensen (2006) and updates. The data may be inaccurate, since no government publishes precise data about its total inventory of nuclear warheads, which includes warheads in various stages of deployment, storage, maintenance and dismantlement, with their status changing as they moved between these stages.

[6] Additional introductive information on fission and thermonuclear weapons and nuclear power reactors can be found, for example, in Charpak, Garwin and Journé (2005).

[7] About one kilogram of fissile material – the amount fissioned in both the Hiroshima and Nagasaki bombs – releases an energy equivalent to the explosion of about 18 thousand tons (18 kilotons) of chemical high explosives.

[8] Along with U-235 and Pu-239, the isotopes U-233, neptunium-237, and americium-241 are able to sustain a chain reaction. While Pu-239 and U-235 are the only fissile materials known to be used in deployed nuclear weapons, the United States has tested designs containing U-233 and France may have experimented with neptunium-237 in nuclear tests (IPMF 2006).

[9] Several technologies have been tried, with different effectiveness. In addition to centrifuges, gaseous diffusion has been for a long time the dominant technology. Compressed uranium hexafluoride gas is pumped through a porous barrier; molecules carrying isotopes with different masses diffuse through the membrane at different rates. When repeated about a thousand times, the method can produce highly enriched uranium hexafluoride molecules. Diffusion plants still operate in the United States and France, but both countries plan to switch to more economical and efficient gas centrifuge plants.

[10] The USA and UK have made public the history of their HEU production and utilization; data for the Soviet Union are based primarily on estimates of the growth of its installed enrichment capacity, taking into account the gradual rise of LEU production for power-reactor fuel.

[11] Almost all of the molybdenum used worldwide is produced by just four companies, all using HEU targets: MDS-Nordion (Canada), Mallinckrodt (Netherlands), Institut National des Radioéléments (Belgium), Nuclear Technology Products (South Africa).

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