14 Nuclear non-proliferation

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14.1 Focus

Nuclear power holds the promise of a sustainable, affordable, carbon-friendly source of energy for the twenty-first century on a scale that can help meet the world's growing need for energy and slow the pace of global climate change. However, a global expansion of nuclear power also poses significant challenges. Nuclear power must be economically competitive, safe, and secure; its waste must be safely disposed of; and, most importantly, the expansion of nuclear power should not lead to further proliferation[1] of nuclear weapons. This chapter provides an overview of the proliferation risks of nuclear power and how they could be managed through a combination of technical, political, and institutional measures.

[1] The term *proliferation* in the nuclear context is used to describe the spread (horizontal proliferation) or further development (vertical proliferation) of nuclear-weapons between or by nation states. The term can also include the spread of nuclear-weapon-usable materials or sensitive nuclear technologies to produce those materials or the spread of sensitive information about nuclear weapons.

14.2 Synopsis

The million-fold increase in energy density in nuclear power compared with other traditional energy sources, such as chemical combustion, makes nuclear energy very attractive for the generation of electricity; however, it is exactly this high energy density that can be used to create weapons of unprecedented power and lethality. The development of commercial nuclear power has, since its inception, had to cope with the prospect of potentially aiding the spread of nuclear weapons. Although commercial nuclear power plants have not directly led to weapon proliferation, the technologies of the nuclear fuel cycle, namely fabricating and enriching fuel, operating the reactors, and dealing with the spent fuel, provides a means for countries to come perilously close to obtaining the fissile materials, ^{235}U and ^{239}Pu, which are required for nuclear weapons. Several countries have developed most of the technical essentials for nuclear weapons under the guise of pursuing nuclear power or research.[2]

The nuclear non-proliferation regime – a fabric of treaties, bilateral and multilateral agreements, organizations, and inspections designed to halt the spread of nuclear weapons while providing access to peaceful uses of atomic energy – has helped to limit the number of states with nuclear weapons. However, this regime is generally agreed to be under severe stress today; some say the world is approaching a "nuclear tipping point" that may usher in unchecked proliferation of weapons and increase the risk of a nuclear catastrophe [1]. Increased interest in expanding nuclear power around the globe, driven by humankind's insatiable demand for energy and concern about global climate change, compounds nuclear proliferation concerns. There is considerable disagreement about whether the risks of nuclear power are worth its benefits.

Whether the risks of a global expansion of nuclear energy can be managed depends not only on technical factors, but also on political, economic, and societal factors [2][3]. The technical challenges overlap with those for nuclear energy (see Chapter 13) and nuclear-waste management (see Chapter 15), except that the focus for nuclear non-proliferation is to examine fuel-cycle technologies and reactor designs and operations that reduce proliferation risk, for example, through greater use of advanced simulation and modeling. Proliferation depends on both capability and intent. Technical measures address only the former; they can mitigate but not eliminate proliferation risks. Hence, a comprehensive set of political, institutional, and technical measures is required in order to manage the incremental risk posed by a global expansion of nuclear power.

[2] The complex relationship between the civil and military use of nuclear technology will be discussed in more detail in supplementary online material available at www.cambridge.org/9781007000230.

14.3 Historical perspective

The awesome destructive power of nuclear weapons demonstrated at Hiroshima and Nagasaki, Japan,[3] convinced President Truman to seek international control of atomic energy shortly after the end of World War II. Toward that end, J. Robert Oppenheimer and colleagues authored the Acheson–Lilienthal Report [4], which warned that "the development of atomic energy for peaceful purposes and the development of atomic energy for bombs are in much of their course interchangeable and interdependent." On June 14, 1946, US diplomat Bernard Baruch presented a plan, based largely on the Acheson–Lilienthal Report, to the United Nations (UN) for the elimination of atomic weapons, together with effective safeguards and inspections [5]. The USSR rejected the Baruch Plan and joined the nuclear age with its first atomic explosion on August 28, 1949.

The Cold War, the British explosion of an atomic bomb, and US demonstration of the hydrogen bomb, a thousand times more powerful than the atomic bomb, led President Eisenhower to try again to rein in what he called the "fearful atomic dilemma" in his December 8, 1953, address to the UN in which he proposed the Atoms for Peace initiative. After initial skepticism, the USSR joined the initiative, leading to the opening of the secret world of nuclear energy to nations around the world that agreed to develop peaceful applications and forego military applications. It also led to the establishment in 1957 of the International Atomic Energy Agency (IAEA), which has the dual mission of promoting global civilian applications of atomic energy around the world and monitoring compliance to ensure their peaceful use.

The first 20 years of the nuclear era saw only France (1960) and China (1964) join the nuclear club. Nevertheless, many industrialized nations, including Sweden and Switzerland, explored the military potential of atomic energy. Initially, the greatest concerns were focused on the potential nuclear aspirations of Germany and Japan. President Kennedy feared that, by the end of the 1960s, the world might have 15–20 nations with nuclear weapons. In 1968, many of the non-nuclear-weapon states (NNWSs), alongside the USA, USSR, and UK, pushed for the adoption of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). One of the key features of the NPT (see Box 14.1) was the establishment of a comprehensive, full-scope safeguards system requiring inspections under the responsibility of the IAEA. It went into effect in 1970, although a number of states, notably China, France, India, Pakistan, Israel, Argentina, Brazil, and South Africa, did not sign at that time.

To date, the non-proliferation regime has had some laudable successes and some major failures. On the success side is the fact that many states use nuclear technology to supply electricity with little carbon release (constituting roughly 14% of the world's electricity production), to provide medical treatments that improve the lives of millions of people, and to conduct scientific research. The NPT has more signatories, 189 in all, than any other treaty, indicating that the non-proliferation norm has become accepted by the overwhelming majority of states. Argentina and Brazil gave up their nuclear weapon programs. Ukraine, Kazakhstan, and Belarus gave up the weapons

[3] These bombs had explosive yields equivalent to approximately 13 and 21 kilotons of TNT, and devastated the two cities, resulting in roughly 200,000 prompt and short-term fatalities.

Box 14.1. The Treaty on the Non-Proliferation of Nuclear Weapons

The three pillars of the NPT (http://www.iaea.org/Publications/Documents/Infcircs/Others/infcirc140.pdf) reflect a bargain among the non-nuclear-weapon states (NNWSs) and between the NNWSs and the nuclear-weapon states (NWSs).

Non-proliferation. All NWSs agree not to transfer, or assist any state in acquiring, nuclear weapons, and all NNWSs agree not to manufacture nuclear weapons themselves and also not to receive such transfer or assistance (Articles I and II). To verify compliance with the treaty, NNWSs accept safeguards by the IAEA to be applied to all source or special fissionable materials in all peaceful nuclear activities within their territory (Article III).

Peaceful use. Article IV gives all NPT member states the right to develop and use nuclear energy for peaceful purposes in conformity with Articles I and II. Moreover, all members in a position to do so agree to cooperate in furthering the development of nuclear energy for peaceful purposes.

Disarmament. Each member agrees to pursue negotiations relating to the end of the nuclear arms race and to nuclear disarmament (Article VI).

Under Article IX.3 of this treaty, an NWS is one that manufactured and exploded a nuclear weapon or other nuclear explosive device prior to January 1, 1967. Hence, the USA, the USSR (nowadays Russia), the UK, France, and China are declared to be NWSs, and all others are NNWSs. The five NWSs are referred to as the P-5 states because, historically, they are also the five permanent members of the UN Security Council and, as such, hold veto power over any Security Council action.

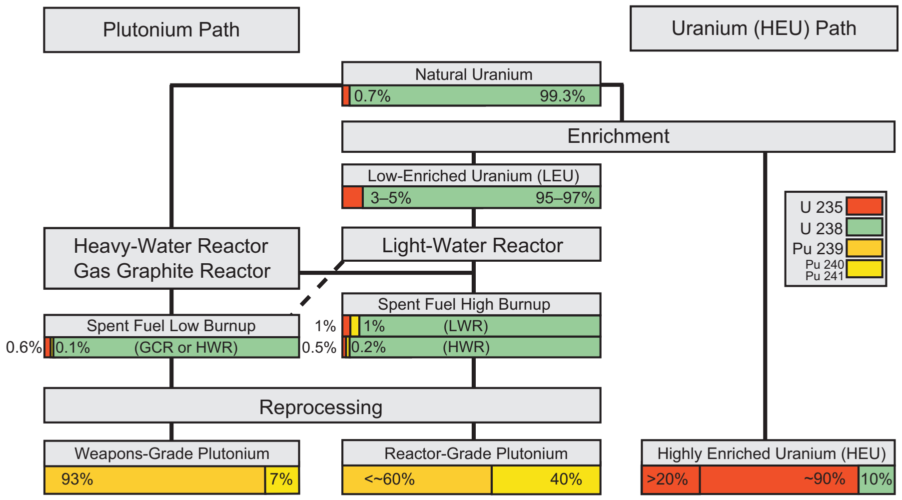

Figure 14.1. Pathways to produce highly enriched uranium (HEU) and plutonium and typical material compositions. Fission products are neglected in the illustration. High burnup for commercial operation is 33 and 7.5 billion watt-days per ton of heavy metal (GW-d per tHM) for light- and heavy-water reactors (LWR and HWR), respectively; low burnup is 1 GW-d per tHM to produce weapons-grade plutonium. The HEU path here refers to weapons-grade HEU GCR (Gas Cooled Reactor).

that they had inherited from the USSR, and South Africa gave up its indigenously developed weapons. In the 1960s, it was believed that 23 countries had nuclear weapons programs; by the 1980s, that number had dropped to 19; and today, it is believed to be 10 [6].

On the failure side, some nuclear weapon programs, such as that of Iraq, have evaded detection from international inspectors within the NPT framework and have procured equipment, materials, technology, and foreign assistance. Moreover, several states have not been integrated into the non-proliferation regime: Israel is believed to have the bomb, India and Pakistan have declared themselves nuclear-armed states, and North Korea withdrew from the treaty and subsequently also declared itself a nuclear-armed state. Concerns about the civil versus military ambiguity of sensitive nuclear technologies continue today, as claims to the right for peaceful use of nuclear energy, based on Article IV of the NPT, could be exploited for military purposes. Finally, progress toward nuclear disarmament, as called for in Article VI, has been insufficient.

14.4 Nuclear non-proliferation

14.4.1 From fissile materials to nuclear weapons

The difficulty of producing fissile materials constitutes the greatest barrier to building nuclear weapons because the two typical pathways (Figure 14.1) – enriching uranium for a highly enriched uranium (HEU) bomb and building reactors and reprocessing spent fuel for a plutonium bomb – are technologically demanding and time-consuming. The USA accomplished both during its crash program for the Manhattan Project in less than three years, but, historically, covert activities beyond the P-5 states, such as those in India, Pakistan, and North Korea,[4] have taken a decade or much longer.

The amount of fissile material needed for a bomb is very small compared with the amounts handled in commercial nuclear programs (see Box 14.2). The HEU for nuclear weapons and military naval reactors has been produced in dedicated enrichment facilities. None of the P-5 states is known to be producing more HEU for weapons today, but other states do (India, Pakistan). In addition, some small, compact reactors, such as those for research or naval vessels, are fueled with uranium enriched at levels above 20%. Dedicated weapons-grade plutonium production reactors use natural uranium fuel in heavy-water-moderated or graphite-moderated reactors (see Figure 14.1). These are operated for short burn cycles in order to yield the most attractive weapons-grade plutonium (higher ^{239}Pu content). All P-5 states produced their weapons-grade plutonium in dedicated production reactors before they built large commercial power reactors. In other countries, such as India, however, the reactors are multipurpose, that is, for research, medical-isotope generation, and plutonium production.[5] Commercial reactors could also in principle be operated to produce weapons-grade plutonium by changing the operation mode from long standing times of the fuel to a very uneconomic short irradiation of the fuel [10].

Information about basic designs of nuclear weapons is now readily available, yet weaponization is more challenging because it requires metallurgical experience with uranium or plutonium, precision machining, expertise

[4] The nuclear stockpile numbers for all nations have historically been classified secret. Only within the past year have the USA and UK declared the numbers openly. The Federation of American Scientists has historically estimated nuclear weapon stockpiles around the world (http://www.carnegieendowment.org/npp/index.cfm?fa=map&id=19238&prog=zgp&proj=znpp).

[5] More details on the dual-use characteristics of reactors to produce plutonium and electricity in the case of the first gas-cooled graphite-moderated reactors in France and the UK, reactors in Russia, and other cases of civil–military ambiguity can be found online at www.cambridge.org/9781107000230.

Box 14.2. Fissile and other nuclear-weapon-usable materials

A technical objective of IAEA safeguards is the timely detection of the diversion of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons. The IAEA defines a significant quantity (SQ) as the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. For plutonium and HEU, these amounts are 8 kg (with <80% ^{238}Pu, because of the high heat generation of this isotope) and 25 kg, respectively, per year [7]. However, declassified documents from the US Department of Energy state that 4 kg of plutonium or ^{233}U is hypothetically sufficient for one nuclear explosive device [8].

Plutonium. The isotope ^{239}Pu can be produced in reactors by neutron capture in fertile ^{238}U. The excited nuclide ^{239}U decays rapidly by double beta decay into ^{239}Pu. ^{239}Pu can capture neutrons to become ^{240}Pu. Subsequent absorption of neutrons leads to ^{241}Pu and ^{242}Pu:

$$^{238}\mathrm{U}(\mathrm{n},\gamma) \longrightarrow {}^{239}\mathrm{U} \xrightarrow{-\beta 23.5min} {}^{239}\mathrm{Np} \xrightarrow{-\beta 2.3565\mathrm{d}} {}^{239}\mathrm{Pu},$$

$$^{239}\mathrm{Pu}(\mathrm{n},\gamma) \longrightarrow {}^{240}\mathrm{Pu}(\mathrm{n},\gamma) \longrightarrow {}^{241}\mathrm{Pu}(\mathrm{n},\gamma) \longrightarrow {}^{242}\mathrm{Pu}.$$

Terminology is Element and Left Superscript is atomic mass and Parenthesis is the particles released in the nuclear reaction (n = neutron, γ = gamma proton, β = electron, time = half life). The longer ^{238}U is exposed to a neutron flux the more plutonium is produced in total. However, the mixture of plutonium isotopes changes, with an increasing share of higher plutonium isotopes (^{240}Pu, ^{241}Pu, ^{242}Pu) and the buildup of ^{238}Pu by several neutron-capture and decay reactions from ^{235}U and ^{238}U:

$$^{235}\mathrm{U}(\mathrm{n},\gamma) \longrightarrow {}^{236}\mathrm{U}(\mathrm{n},\gamma) \longrightarrow$$
$$^{237}\mathrm{U} \xrightarrow{-\beta 6.7\mathrm{d}} {}^{237}\mathrm{Np}(\mathrm{n},\gamma) \longrightarrow {}^{238}\mathrm{Np} \xrightarrow{-\beta 2.1\mathrm{d}} {}^{238}\mathrm{Pu},$$

$$^{238}\mathrm{U}(\mathrm{n},2\mathrm{n}) \longrightarrow {}^{237}U \xrightarrow{-\beta 6.7\mathrm{d}} {}^{237}\mathrm{Np}(\mathrm{n},\gamma) \longrightarrow$$
$$^{238}\mathrm{Np} \xrightarrow{-\beta 2.1\mathrm{d}} {}^{238}\mathrm{Pu}.$$

Weapons-grade plutonium is generally defined as >93% ^{239}Pu in the isotopic mixture, typically extracted from dedicated plutonium-production reactors in which the ^{239}Pu content is much higher than that of typical spent commercial nuclear fuel because of the short exposure to neutron irradiation. Longer exposure, such as in a commercial fuel cycle, produces more of the higher plutonium isotopes, neptunium, and americium.

There is still disagreement in the literature about the weapons utility of *reactor-grade plutonium* in which the percentage of the fissile isotopes ^{239}Pu and ^{241}Pu can be as low as 50% or so. The mix of plutonium isotopes makes reactor-grade plutonium somewhat less attractive for weapons from a nuclear physics standpoint and considerably more difficult for engineering and manufacturing because of the increased heat mainly from ^{238}Pu and radioactivity of ^{238}Pu and ^{240}Pu. Bathke and co-workers recently made the case that any plutonium produced in current fuel cycles and reprocessing schemes is sufficiently attractive for nuclear weapons, even if it is mixed with other transuranium elements (Np, Am, Cm), that it warrants safeguards and protection [9].

^{235}Uranium. *Highly enriched uranium (HEU)* is defined as ≥20% ^{235}U. Weapons-grade uranium is generally defined as roughly 90% ^{235}U, but any level above 20% can theoretically be used to make a bomb. **Low-enriched uranium (LEU)** is defined as <20% ^{235}U and natural uranium ore is 0.71% ^{235}U, with the remainder being ^{238}U.

^{233}Uranium. In addition to ^{235}U and ^{239}Pu, the IAEA includes the fissile isotope ^{233}U in the category of "special fissionable material" or "direct-use material" [7] requiring safeguards and protection. It can be produced in reactors in an analogous manner to ^{239}Pu, except starting with ^{232}Th instead of ^{238}U as the fertile reactor fuel:

$$^{232}\mathrm{Th}(\mathrm{n},\gamma) \longrightarrow {}^{233}\mathrm{Th} \xrightarrow{-\beta 22min} {}^{233}\mathrm{Pa} \xrightarrow{-\beta 27d} {}^{233}U.$$

The IAEA defines 8 kg of ^{233}U as 1 SQ. However, there is no indication of any nation currently using ^{233}U in a nuclear arsenal.

Alternative nuclear materials. ^{237}Np, ^{241}Am, and ^{243}Am, which are present in typical spent fuel, are sometimes referred to as alternative nuclear materials, since they have nuclear properties that make them potentially suitable for nuclear weapons. [7]

Tritium can be used in small quantities to enhance the yield of a nuclear weapon. Tritium is not subject to IAEA safeguards, although it is subject to export controls in accordance with multilateral agreements and national-level controls.

Box 14.3. Explosive mechanisms of pure fission weapons

The first nuclear weapons built, and the only type ever used, were pure fission bombs. They used two different mechanisms, as shown in Figure 14.2, to achieve critical mass for a self-sustaining chain reaction.

Gun-type assembly. This weapon design is technologically straightforward: two-subcritical masses of HEU are impacted at high speed in a gun barrel. The bomb detonated over Hiroshima was an HEU-fueled gun-assembly device.

Implosion device. The gun-type assembly method turns out to be too slow for plutonium because enough neutrons are generated by spontaneous fission of the minor isotope ^{240}Pu in weapons-grade plutonium to pre-initiate a nuclear chain reaction, resulting in merely a "fizzle" rather than a full-scale explosion. Instead, a subcritical, spherical mass of plutonium is imploded with high explosives to reach much higher velocities and a full nuclear explosion. The bomb detonated at Nagasaki was a plutonium-fueled implosion device.

More advanced explosive mechanisms have since been developed and tested, including a fusion-boosted fission assembly method and the two-stage thermonuclear assembly method.

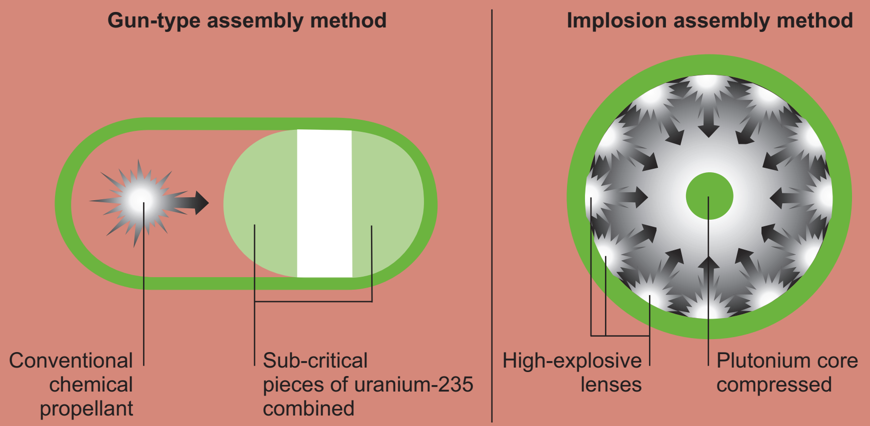

Figure 14.2. Mechanisms used to achieve critical mass for a self-sustaining chain reaction in a pure fission weapon: (left) gun-type and (right) implosion assembly methods. From [11].

with propellants or explosives, detonators, initiators to inject neutrons, and computational capabilities. Primitive bombs of the types exploded in Japan (see Box 14.3) are generally viewed as being within reach of technologically proficient nations once they have mastered the ability to make fissile materials. For example, South Africa and Pakistan developed HEU-fueled bombs, and North Korea opted for the plutonium route.

Historically, all nations developing a nuclear arsenal tested their early weapon designs, although there is considerable ambiguity for Israel and South Africa [12][13]. Testing is important for advanced designs. Modern thermonuclear warheads are among the most complex technological devices in the world. The miniaturization of a nuclear warhead so that it can be carried on an intercontinental ballistic missile (ICBM) constitutes a formidable technical challenge that only the P-5 states have mastered to date. Some of the other states with nuclear weapons might have mastered warheads small enough to mount on short- or medium-range missiles, but they do not possess ICBMs and are believed not to have produced ICBM-compatible miniaturized designs. Sub-national groups or terrorists could instead settle for a van, boat, or airplane if they are able to acquire a nuclear device or make an improvised one.

14.4.2 Nuclear fuel cycle and proliferation concerns

Proliferation concerns depend on the specifics of the fuel cycle, particularly the front end (uranium enrichment) and back end (reprocessing), which provide opportunities for access to weapon-usable materials (Figure 14.1).

The method of choice today for uranium enrichment uses gas-centrifuge technology in which the lighter ^{235}U gas in the form of uranium hexafluoride is separated from the heavier ^{238}U in cascades of rapidly spinning centrifuges. Once a state acquires the capability to enrich uranium to the typical level needed for light-water reactors (LWRs), namely 3%–5% ^{235}U, the technical capability to continue enrichment to weapons-grade levels of roughly 90% inherently exists. Also, by producing LEU of 3%–5% enrichment, much of the separative work (approximately 70%–88%) necessary for getting to weapons grade is already done. Only a fraction of the cascades used for a full-scale commercial enrichment facility would need to be diverted or constructed to produce sufficient weapons-grade HEU for a few bombs per year. At the back end, for some fuel cycles, plutonium is extracted from spent fuel by reprocessing, typically using the PUREX (plutonium–uranium recovery by extraction) process (see Chapter 13) [14].

As explained in Chapter 13, the open, or once-through, fuel cycle with LWRs forms the backbone of the commercial nuclear power industry. The primary proliferation concerns are associated with uranium enrichment. The back end of the once-through fuel cycle is generally considered to be more proliferation-resistant than the back ends of other fuel cycles because the spent fuel is highly radioactive and is stored for eventual disposal without the separation of reactor-grade plutonium. This spent fuel is considered to remain self-protecting for 100 years or more.

Variations of the open fuel cycle include heavy-water reactors (HWRs) and gas-cooled reactors (GCRs). Heavy-water reactors can operate on natural uranium (0.7% ^{235}U), thus avoiding the need for enrichment (although some advanced HWRs might use 1%–2% ^{235}U). However, more plutonium, with higher ^{239}Pu content, is produced than for similar LWR burnups,[6] and spent fuel is removed from the reactor continuously, which makes safeguards more challenging than for LWRs.

Several countries have modified the open fuel cycle by reprocessing the spent fuel from LWRs and using the resultant plutonium in a uranium–plutonium mixed oxide (MOX) fuel that can be burned directly. Although the reactor-grade plutonium produced in such fuel cycles is not very attractive for weapons, its use in weapons is not impossible, and it must be safeguarded from potential diversion and protected during transportation.

Fast reactors operate at high neutron energy and are able to nearly fully consume the energy content of the fuel with several passes through the reactor. They can also operate in a "breeding" mode, in which more fissile material is produced than is consumed by the reactor. The proliferation concerns for such reactors stem from the fact that a great deal of plutonium is produced with high ^{239}Pu content and, in current schemes, it is separated, hence presenting significant security and safeguards challenges.

Thorium-fueled reactors are of interest as an alternative to the use of uranium. Proliferation concerns for this technology stem from the capture of a neutron by fertile ^{232}Th, creating the fissile isotope ^{233}U. As ^{233}U is bred, small amounts (part-per-million quantities) of ^{232}U are also produced. With a half-life of only 73.6 years and strong gamma-ray emission from its daughters, most notably the 2.6-MeV gamma-ray from ^{208}Tl, ^{232}U could provide some proliferation resistance relative to the uranium fuel cycle as handling becomes more difficult [15].

[6] Burnup is a nuclear engineering term for the power released by fission events in a given mass of the fuel. Since most fission events in uranium fuel stem from fission of ^{235}U, the burnup is proportional to the amount of ^{235}U consumed to produce energy.

14.4.3 Potential pathways to weapons from the commercial fuel cycle

The commercial fuel cycle and the associated research infrastructure can potentially lead to weapons proliferation through several pathways.

(1) A state's declared commercial or research facilities could be diverted to produce weapons-grade materials for bombs, either covertly or by leaving the NPT regime. The expertise and equipment from commercial operations or associated research programs could be used to develop clandestine facilities dedicated to the production of weapons material.

(2) Fissile material from the commercial fuel cycle or research facilities could be diverted or stolen to make nuclear weapons.

(3) A commercial nuclear infrastructure could constitute a latent nuclear-weapon capability; that is, a nation could produce fissile materials under the umbrella of a purely civilian program, or it could develop the necessary facilities and know-how to do so at a later time. Japan and Germany are examples of the first, and Iran is an example of the second.

Although none of the pathways can be ruled out, commercial nuclear power programs have not been used directly to develop nuclear weapons to date. Section 14.4.5 discusses how this situation could change as global nuclear power expands.

14.4.4 Current proliferation threats

Threats from emerging and aspiring nuclear-weapon states

To build a nuclear arsenal, countries need both capability and intent. Nuclear information has become broadly accessible, and the technological threshold for sensitive nuclear technologies (i.e., enrichment and reprocessing) is within reach of more countries. Rather than ushering in global peace, the end of the Cold War might have provided greater motivation for countries to develop their own nuclear weapons. Some countries saw their security guarantees evaporate with the dissolution of the Soviet bloc or the reordering of US foreign policy priorities. Others faced

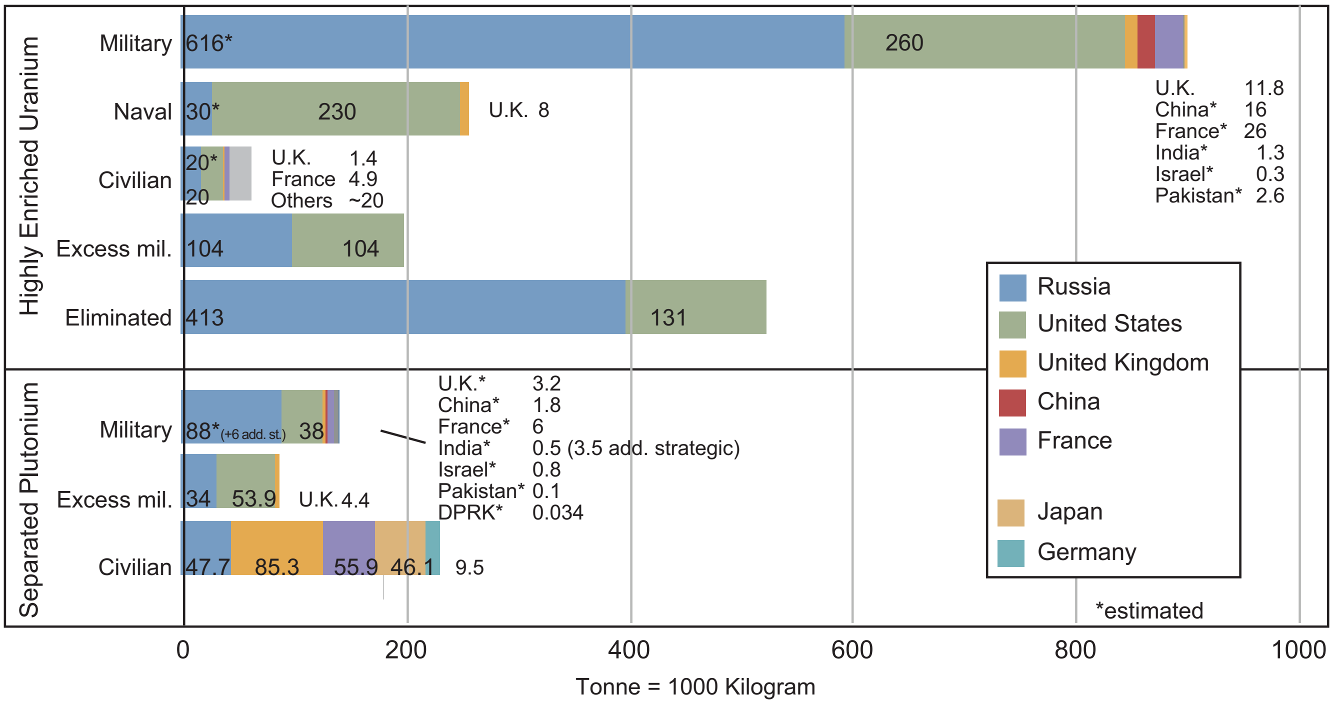

Figure 14.3. Estimated national stockpiles of highly enriched uranium and separated plutonium. Uncertainties in the military stockpiles for China, France, India, Israel, Pakistan, and Russia are on the order of 20%. DPRK, Democratic People's Republic of Korea. (See the report of the IPFM [11] for data and a detailed discussion.) *means the number estimated and grey is others.

new regional hostilities, and some felt threatened by a world apparently moving toward American hegemony.

During the past 12 years, India, Pakistan, and North Korea have declared themselves to be nuclear powers by testing nuclear devices. Following Pakistan's acquisition of the bomb, its leading scientist, A. Q. Khan, built a proliferation black-market network [16] that sold nuclear technologies and know-how to North Korea, Iran, and Libya. North Korea provided nuclear assistance to Syria and Libya, and possibly to Iran and Myanmar. For more details on some countries see Appendix 14.8.

These developments are not directly associated with commercial nuclear power, but they have rightfully caused alarm and concern that the international non-proliferation regime might be collapsing, despite the fact that there are fewer states with nuclear weapons than had been projected 50 years ago and fewer active nuclear-weapons programs than existed 40 years ago.

Threats from fissile-material stockpiles

Currently, enormous quantities of fissile material are available and pose a proliferation threat should they fall into the hands of nuclear terrorists or be used in weapon programs by nation states. Estimates of these materials around the world (see Figure 14.3) have been provided by the International Panel on Fissile Materials (IPFM) [11].

Highly enriched uranium (enriched in ^{235}u) is not used in commercial nuclear fuel cycles. Most of the 1,850 t [1 tonne (t) = 1,000 kg] of HEU in the world is housed in military programs (in weapons programs, in naval reactors, or declared in excess of military needs). About 64 t of HEU, at levels of 36%–93%, is currently used in the civilian research-reactor fuel cycle, of which roughly 9 t is under IAEA safeguards in non-nuclear-weapon states. The recognition of the need to minimize the civilian use of HEU has led to several activities to improve safeguards, return fresh and spent HEU fuel to the original supplier country, and to convert reactors to use LEU (<20% enrichment).

Half of the 500 t of separated plutonium is weapons-grade plutonium and originated from military programs. This plutonium is very attractive for weapon purposes and is mostly in the possession of Russia and the USA, which have declared parts of it excess to their needs for military use. The other 250 t is civil separated reactor-grade plutonium produced in commercial power plants and subsequently reprocessed (see Figure 14.3). As indicated in Box 14.2, the isotopic composition of plutonium from commercial reactors is not ideal, and hence this plutonium presents significant, but not insurmountable, challenges for bomb manufacture.

More than 50 countries have spent fuel from commercial or research reactors. To the best of our knowledge, no commercial plutonium has been diverted for weapon use. Between 1993 and 2007, the IAEA reported 18 illicit trafficking incidents involving HEU and separated plutonium [17].

Nuclear terrorism threats

Concerns about separated plutonium and HEU from research reactors around the world highlight the increased threat of nuclear terrorism, particularly because HEU can be used in a gun-assembly nuclear device, which is technologically much simpler than an implosion device. Concerns about the potential nexus of international terrorism and sub-national groups and nuclear weapons have grown since the terrorist attacks on New York City and the Pentagon on September 11, 2001 (known as 9/11). The most serious threat is the acquisition of fissile materials, by either theft or diversion, by such groups and the subsequent building of an improvised nuclear device. Even an imperfect nuclear device of a few kilotons or lower detonated in one of the world's megacities could kill 10,000 or more people and cause global disruption on an unprecedented scale. The primary concern is the protection and safeguarding of these fissile materials to keep them out of the hands of terrorists. The global nuclear security summit held in Washington, DC, in 2010 demonstrated that the importance of doing so is now generally appreciated, but the technical difficulty of doing so is not [18].

Commercial nuclear power contributes rather little to the nuclear-terrorism threat today, because fissile materials from commercial operations are contained in spent fuel, well protected, and not very attractive to terrorists. However, there is considerable concern about the security of commercially separated plutonium. As noted above, transportation of separated plutonium or MOX is a security concern. For example, Japan regularly ships its spent fuel to France for reprocessing and receives separated plutonium and waste in return. Shipping the separated plutonium in the form of MOX fuel does not improve the proliferation resistance significantly. Such issues could be addressed by co-locating reactor facilities with fuel fabrication.

Nuclear power plants and fuel-cycle facilities can also be targets of nuclear sabotage or provide materials for radiological dispersal devices, so-called dirty bombs [19][20]. These events do not yield a nuclear explosion or damage on the scale of such an explosion. Although both sabotage and radiological dispersal could cause enormous disruption, they do not constitute nuclear proliferation and, therefore, are not considered further here.

14.4.5 Challenges posed by a global expansion of nuclear power

The resurgence of interest in commercial nuclear power around the world presents a challenge and an opportunity to this generation of scientists and engineers. In the USA, electric utilities have expressed interest in the construction of 26 new nuclear power plants – a dramatic change from the past 30 years. China, India, and Russia have ambitious plans for expansion of nuclear power in the coming decades. In addition, more than 60 IAEA member states have expressed interest in starting new nuclear power programs, although only a dozen or so are seriously pursuing new reactors at this time.

It remains to be seen how the Fukushima-Daiichi nuclear accident in March 2011, will affect global expansion of nuclear power. In China, for example, the Japanese reactor accident is predicted to delay China's ambitious nuclear reactor build-up, but not dramatically curtail it.

In assessing how the spread of nuclear power might impact global proliferation, it is important to differentiate the growth of nuclear power in countries that already use it from the spread of nuclear power to additional countries [21]. Aspirant nuclear states might have significantly poorer governance, resulting in less safe and secure nuclear power, and a much lower aggregate democracy score, increasing their likeliness to violate their NPT obligations. These states also rank high on the list of states having suffered serious terrorist attacks during the previous five years, thereby representing a serious proliferation challenge if they pursue nuclear power with fuel-cycle facilities.

A significant expansion of nuclear power could also lead to concerns about uranium shortages or tensions caused by the distribution of uranium resources, which, in turn, could lead more countries to pursue national enrichment and closed fuel cycles with breeder reactors, fueled with either uranium or thorium. India is a good case in point, insofar as its concern about nuclear fuel supply has led it to a strategy that is heavily reliant on plutonium breeder reactors, followed by thorium-fueled reactors, although other factors likely influenced this strategy.

In addition, an expansion of nuclear power could lead to a significant shift in nuclear-reactor and fuel-cycle suppliers around the world. As more countries enter the nuclear technology supply chain for commercial purposes, it might be more difficult to prevent clandestine sales of such equipment. Finally, a substantial increase in the number of states aspiring to nuclear power and fuel-cycle technologies would greatly overburden the monitoring and inspection capabilities of the IAEA. In addition to these non-proliferation issues, nuclear-reactor safety and protection of facilities from nuclear sabotage will become more challenging as the number of reactors and fuel-cycle facilities increases.

Proliferation risks must be mitigated by a combination of technical, institutional, and political measures. The residual risk must then be compared with the benefits achieved by expanded global nuclear power. The private sector will look primarily at economics, whereas governments must make the call for safety, security, and global climate change. The next section discusses potential technical measures with a focus on materials technologies.

14.4.6 Proliferation countermeasures

In general, one can categorize measures to improve fuel-cycle resistance to proliferation as intrinsic or extrinsic. Intrinsic measures rely on technical means, such as incorporation of material attributes (e.g., increased radiation dose from fission-product addition to nuclear fuel or removal of fissile-material precursors) that provide some additional barrier to illegitimate use or general technical design features of facilities. In addition, there are technical components to improving institutional barriers to proliferation – for example, better technologies for nuclear detection, monitoring, and nuclear forensics. Extrinsic measures rely on institutional and political measures to safeguard and secure material, control exports, and enforce international norms. Neither extrinsic nor intrinsic measures alone are sufficient to increase the confidence in or provide independent verification of a nation's peaceful application of nuclear energy.

The technical community has pursued proliferation-resistant reactors and fuel cycles for decades, but it is now generally acknowledged that none are proliferation-proof [22][23][24]. Yet, some are more proliferation-resistant than others, and hence methodologies to compare proliferation risks of specific technologies continue to be developed [25][26].

Examples of technical countermeasures and materials research opportunities

On the technical side, operating within institutional and political frameworks, are verification and accounting activities engaged in by both the host state and the international community, primarily the IAEA. Direct accounting of nuclear material requires a formal materials protection, control, and accountancy (MPC&A) program, which, in turn, relies on measurement techniques. Doyle provides a comprehensive treatment of the technical issues related to non-proliferation [27]. Radiation detection provides the basis for many of the techniques used in MPC&A and is covered in detail by Knoll [28].

Advanced measurement techniques. An important aspect of verification relies on non-destructive assay (NDA) measurements involving radiation detection [29]. Uranium and plutonium (as well as thorium) are radioactive and present a variety of usable signatures. In particular, X- and gamma-rays and neutrons are used for detection and quantification because of their greater penetrating power as compared with alpha- and beta-radiation. ^{235}U has gamma-rays in the energy range of 100 keV to 200 keV, while isotopes of plutonium emit strongly in the 100–600-keV region. ^{238}U has a gamma-ray at 1 MeV. Plutonium, particularly the even isotopes, undergoes spontaneous fission. Thermal and fast neutrons can induce fission in ^{235}U, whereas ^{238}U undergoes neutron-induced fission only above a threshold of about 0.6 MeV. Fission creates multiple neutrons per event and is the basis of the most accurate NDA methods exploiting the neutron signature. Radiation detectors operate on the basis of charge creation and collection. X- and gamma-rays ionize matter directly through the Compton and photoelectric effects, whereas neutrons create charge by undergoing nuclear reactions (thermal) or elastic scattering (fast).

Most NDA methods based on neutron detection rely on the ^{3}He neutron-capture reaction, which has a higher cross section than that of either ^{10}B or ^{6}Li capture and little sensitivity to gamma-rays. Detector manufacturers have long relied on the supply of ^{3}He derived from the decay of tritium used in nuclear weapons. One outcome of nuclear arms reduction has been a reduced need for tritium for the remaining nuclear arsenal and, thereby, a reduced supply of ^{3}He. This, combined with a great increase in demand in response to the 9/11 attacks, has created a global crisis in ^{3}He supply. This shortage has implications for nuclear non-proliferation, particularly for safeguards, where neutron counting has been a core measurement technique for decades. In particular, time-correlation analysis based on thermal-neutron detection is the most accurate measurement technique for bulk samples [30].

Alternative technologies being investigated include gas proportional counters, and semiconductor and scintillation technologies utilizing primarily ^{10}B or ^{6}Li. Boron-lined ^{3}He proportional counters were developed for neutron detection in very high (100 roentgen per h) gamma-ray fields. An extension of this technology, where ^{3}He is replaced with a low-atomic-number (low-Z) charge-carrier gas is currently under development. The key issue is one of increasing the surface area (and therefore detection efficiency) and still maintaining both the ability to detect the alpha particle from the ^{10}B(n,α)^{7}Li (α particle is the He nucleus) reaction and the long-term stability of the thin coating. Advanced materials for neutron detection also include semiconductors. The most mature of these devices uses a Si pin diode with etched channels containing ^{10}B or ^{6}Li as the active element. Advances in material science to control parameters such as purity, structure, and bonding will be needed in order to take these technologies out of the laboratory and into practical field application.

Improvements in gamma-ray detectors are also needed, primarily driven by the desire to achieve good energy resolution (for accurate nuclide determination) while avoiding the need for cryogenic operation (to simplify field use and cost). High-purity germanium (HPGe) is the standard in gamma-ray spectroscopy. It can be manufactured in large crystals with very high purity and has excellent energy resolution, but it requires liquid nitrogen (77 K) or equivalent mechanical cooling and is expensive. Sodium iodide is a room-temperature detector material with moderate energy resolution. Research on new materials, both scintillators and semiconductors, is needed and ongoing. One very promising new scintillator material is CLYL (Cs_2LiCl_6:Ce) [31], which not only has demonstrated better resolution than NaI but also provides neutron detection via ^{6}Li capture. Good pulse-shape discrimination for neutrons and gamma-rays has also been observed. In addition, the application of advanced modeling and simulation techniques is beginning to provide a more systematic approach to materials discovery [32][33]. This is a rich area to which advances in materials science have increasingly contributed.

When the highest possible accuracy or sensitivity is required, analytical chemistry-based measurement techniques are used. These methods are generically called destructive analysis because the sample being analyzed is consumed in the analysis process. Such techniques are best suited to situations where small portions of material can be removed and then analyzed, such as in bulk processing facilities (mining, fuel fabrication, reprocessing). The IAEA routinely extracts samples for chemical analysis as part of its verification activities. Under the Additional Protocol to the NPT (discussed further below), wide-area environmental sampling is allowed as part of the verification of the completeness of a country's declared nuclear program. Advances in materials science and associated chemical separation methods and instrumentation, such as fission-track thermal-ionization mass spectrometry and inductively coupled plasma mass spectrometry, have enabled analysis of individual particles. These methods offer the ultimate accuracy and sensitivity, but are extremely time-consuming and require extensive sample preparation. Continued development is needed in order to allow these and related techniques to be applied more extensively by moving them out of the laboratory and into the field.

Other technical issues. A host of other technical issues arise under the expansion and evolution of the nuclear fuel cycle. First-principles modeling and simulation will play an increasingly important role both for basic materials development and for optimization of the non-proliferation benefits of new fuel-cycle technologies. In general, advanced concepts involve materials that must withstand environments with higher radiation doses, higher temperatures and pressures, and higher corrosion [34]. Many of the materials issues associated with these advanced concepts and approaches are discussed in Chapters 13 and 15. Here, the non-proliferation aspects of such systems are addressed, specifically, small and medium-sized reactors, increasing fuel burnup, fast reactors, and advanced fuels and reprocessing.

In many cases, countries or locations that would benefit the most from access to nuclear power do not possess the infrastructure to support a traditional 1,000-MWe power reactor. Smaller, possibly sealed, reactors could be appealing in addressing this issue and offer an opportunity for strengthening the non-proliferation regime through integrating advanced materials, engineered systems, and advanced monitoring concepts. Interest in small modular reactors (SMRs) is also being revived in the USA especially because such reactors may help to reduce the enormous up-front financial barriers for new power-plant construction and might also provide an effective way for the USA to regain a global role in nuclear power export. In turn, these concepts place a major burden on materials. For example, a reactor that is delivered as a complete module to a site, operated for a number of years, and simply returned for replacement offers some obvious non-proliferation benefits (no access to fresh or spent fuel during normal operation, no requirement for enrichment or reprocessing capability in the receiving nation, reduction of safeguards verification to maintaining continuity of knowledge of an item and its sealed status) and requires advanced fuels and other materials to make the lifetime of such a system practical. Toward this end, advances in integrated monitoring, advanced sensors tied to global positioning, and central control are needed to enhance remote monitoring.

Increasing the utilization of uranium fuel also provides benefits to larger power reactors in terms of longer cycle times and reduced waste (see Chapters 13 and 15 for details), and much work has been done to examine these approaches. Reactor concepts that employ a pebble-bed approach and have fuel cycling through the reactor present a challenge to monitoring, because the volume is high and fuel is mixed with non-fuel materials, with both traveling in and out of the reactor core [35]. Inert-matrix fuels are being investigated as a means to burn plutonium in the absence of ^{238}U (which creates plutonium through neutron capture) and would be compatible with existing reactor designs, including those that utilize MOX fuel [36]. Advanced monitoring equipment that is capable of operating in real time and in a harsh environment is needed.

Fast reactors (Chapter 13) present a particular challenge for maintaining the continuity of knowledge in the case of liquid-metal cooling, where standard optical monitoring of the core cannot be implemented [37]. One technology that has been investigated is based on acoustic imaging of fuel bundles in liquid sodium. Sensors like this must survive and operate in a very harsh thermal–mechanical and radiation environment. Fundamental understanding of radiation damage leading to self-healing materials, for example, could play an important role in providing additional robustness for new fuel-cycle concepts.

Some countries are also exploring pyroprocessing instead of the typical aqueous PUREX process in an attempt to provide better proliferation resistance of the reprocessed actinide mixture. The US Advanced Fuel Cycle Initiative (AFCI) examined several schemes (aqueous and pyrochemical Chapter 13) that involve co-extraction of some of the minor actinides and fission products with plutonium. Some of these schemes represent better proliferation resistance in terms of material attractiveness, but none is proliferation-proof. Significant advances in enhancing proliferation resistance during reprocessing will most likely have to await the development of new reactors and new fuels for which better proliferation characteristics are designed in at the beginning, rather than trying to retrofit existing reactors and fuels.

The evolution of the nuclear fuel cycle includes a variety of advanced fuels and reprocessing techniques, which may present opportunities to apply technical advances in materials protection, control, and accounting. In particular, bulk processing facilities will need not only material-specific instruments and techniques, but also real-time, continuous operation in a variety of operating environments. Gains can also be realized in an integrated-systems sense by relating signature information across facilities. How to quantitatively measure the actinide content of spent fuel is being researched [38]. Many advanced concepts will require remote handling facilities for fuel fabrication.

Institutional and political countermeasures

Technical measures address mostly the supply side of nuclear proliferation. Effectively preventing proliferation requires control of supply, reduction of demand, and readiness to respond. Institutional and political measures must be combined with technical measures to address all three.

Controlling supply. Controlling the spread of enrichment and reprocessing facilities reduces proliferation risks. Such efforts must consider the full range of the fuel cycle, IAEA controls, and exports. Currently, the free-market system is working adequately to provide enrichment capacity, but attempts to restrict such facilities to countries that currently have them while expanding nuclear power globally are problematic. Serious consideration of limiting the number of countries that should be allowed to run enrichment facilities has prompted Brazil, South Africa, Australia, and others to either declare their intent to establish enrichment facilities or expand what they have.

A variety of multinational arrangements have been proposed in recent years to ensure reliable access at competitive market prices without exacerbating proliferation concerns [39]. Three categories can be identified: (1) multinational ownership and operation of uranium enrichment facilities, (2) multinational or regional fuel procurement partnerships, and (3) multinational or international fuel reserves or fuel banks. Some multinational schemes for both front- and back-end facilities were proposed in the 1970s and 1980s but never came to fruition.

There has been no case in which an NPT State party has had to shut down a commercial reactor because it could not get fuel. Still, the insistence of some states on developing their own national enrichment facilities shows the shortcoming of the market approach. The reasons for this range from economic interests to domestic politics and state pride and from protection of technology to retention of a latent nuclear-weapon option. To find a lasting solution to reducing the incentives for countries to build their own enrichment plants, it is important to pay attention to what the user states consider to be adequate guarantees rather than simply having the supplier states dictate the solution.

Some of the options in Chapter 15 to deal with spent fuel are amenable to international solutions, which could increase proliferation resistance, for example, monitored interim storage of spent fuel or regional geological repositories. However, such schemes will most likely require having some defined solution to long-term disposition. In fact, the most attractive option for many countries might be a fuel-leasing service that provides both enriched fuel and take-back of the spent fuel and waste. Only Russia is capable both technically and legally of providing such services today. Cooperation on international or regional geological disposition would also be desirable but has not gained much support to date.

Reprocessing is the most proliferation-sensitive back-end technology. The total world capacity for reprocessing is expected to exceed demand unless plutonium recycling becomes more economically attractive [40]. All current reprocessing facilities are national facilities run by governments or state-controlled corporations, and there is no experience with multinational facilities.

Many in the non-proliferation community continue to stress that the best protection on the back end is to forego reprocessing – that is, to practice only an open fuel cycle [11][41]. However, much as was the case in the late 1970s, when the Ford and Carter administrations chose to end reprocessing in the USA, some of the key nuclear states see it very differently. Of particular note are France, Russia, Japan, India, and most likely China. Consequently, this problem must be considered from a greater global perspective to better understand what the principal driving forces are for other nuclear-power countries to pursue reprocessing.

Strengthening international safeguards continues to be a critical step to providing better proliferation countermeasures. In 2009, the IAEA applied safeguards in 170 countries with safeguards agreements in place. Eighty-nine of these states had both comprehensive safeguards agreements and additional protocols in place [42]. The objective is to detect diversion of significant quantities of nuclear material at declared facilities and clandestine nuclear-weapons activities under the Additional Protocol as early as possible, or at least to introduce a measure of uncertainty into a violating country's calculus about the probability of being detected. Such nations typically aim to develop a capability as quickly as possible while keeping the probability of detection as small as possible.

Iraq's nuclear-weapons program before the Gulf War demonstrated how comprehensive safeguards agreements were inadequate because they were directed at verifying only the correctness of a country's declaration of nuclear facilities and materials. The IAEA developed the Additional Protocol, which provides greater rights of access to suspect locations, allowing inspections on short notice, environmental sampling, and remote monitoring, to help verify the completeness of the declaration. However, the Additional Protocol remains voluntary and is in force in only 104 states as of December 2010, with many key countries not having ratified it.

Environmental monitoring is a powerful tool that can help to provide effective nuclear safeguards. However, there are rich opportunities for contributions from research in analytical and nuclear chemistry and materials science to address the associated technical challenges, including developing effective remote monitoring systems, better detectors, and improved nuclear forensics capabilities.

Strengthening existing mechanisms that control supply is imperative. This must be done in conjunction with the strengthening of export control laws in potential technology-supplier countries and the development of better domestic legislative bases for export control. The success of the A. Q. Khan network in circumventing existing supply controls demonstrates that one must constantly adapt control and legal mechanisms as these networks evolve [16]. Detection and attribution are important and require enhanced technical capabilities both in detector technology and nuclear forensics.

Reducing demand. Efforts to control the supply side of proliferation are necessary, but not sufficient. The motivations for countries to seek nuclear weapons must be better understood to limit the demand for these weapons. Three models have been suggested to analyze the nuclear-weapons aspirations of a state [43][44]: the security model, the domestic-politics model, and the norms model. The security model calls for states to build nuclear weapons to increase their security against foreign threats, especially nuclear threats. The domestic-politics model posits that nuclear weapons might serve the bureaucratic or political interests of individual actors or coalitions of actors, such as the military or the nuclear establishment, who can influence the state's decision making. The norms model views nuclear decisions as also serving important symbolic functions externally – both shaping and reflecting a state's identity in relation to the international community.

Security concerns have been the primary driving factors for the acquisition of nuclear weapons, although in cases such as the UK, France, and India international aspirations and domestic factors played substantial roles [1][45][46]. The principal approaches most studies highlight for reducing demand based on insecurity are security assurances, regional conflict-resolution initiatives, nuclear-weapons-free zones (five of which exist today, with four of them spanning the entire Southern Hemisphere; see http://www.armscontrol.org/factsheets/nwfz), and efforts by the P-5 states to reduce the salience of nuclear weapons. Domestic issues are more complex to ascertain and difficult to control, so a focus on domestic politics is unlikely to prove effective or efficient in reducing demand. In contrast, international norms do play an important role. Most of the non-proliferation community is concerned that the rules-based order of the nuclear non-proliferation regime is being steadily eroded, however, so efforts must be made to strengthen such norms.

Nuclear disarmament toward a nuclear-weapons-free world as stipulated in Article VI of the NPT is important and might help to reduce demand, but many consider this a distant goal. Even working toward this goal will pose formidable technical challenges in verifying nuclear arsenals and fissile-material stockpiles, as well as providing adequate security.

Strengthening enforcement and response. Enforcement and appropriate response continue to be the weakest link in the non-proliferation fabric. It is the IAEA Board of Governors' job to report non-compliance to all members and to the Security Council and General Assembly of the United Nations for action. Sanctions are one of the main tools, but often, they have not demonstrably changed nuclear ambitions, in part because the P-5 countries have different views of the effectiveness of sanctions and different strategic interests. However, most agree that a more effective consensus must be developed to implement serious penalties for countries violating their NPT obligations. Likewise, there is general consensus that withdrawal from the NPT should involve some additional legal hurdles for those who intentionally violate their obligations while accepting nuclear assistance and then simply withdraw to build nuclear weapons, as North Korea apparently did.

One interesting aspect that supports the non-proliferation regime is that countries that have well-developed and globally connected economies might simply have too much to lose to violate their obligations or break their agreements.

14.5 Summary

Nuclear non-proliferation issues, like those for nuclear energy and nuclear-waste disposal, depend on institutional and political considerations in addition to the technical issues that are the focus of this book. The technical non-proliferation challenges in general and the materials challenges in particular depend directly on the technical nature of the nuclear fuel cycle, reactor design and operations, and recycling and waste disposal, as discussed in Chapters 13 and 15. The institutional and political issues are similarly intertwined. There are technical measures that will increase proliferation resistance, but none will make reactors and fuel cycles proliferation-proof. Hence, nuclear non-proliferation requires detailed analysis of the interplay of technical, institutional, and political countermeasures to proliferation.

Despite the many serious challenges that the non-proliferation regime faces today, the non-proliferation treaty and regime appear to have a "hidden robustness" [1] that prevents the world from sliding toward a "tipping point" of unchecked proliferation. However, a global expansion of nuclear power can be managed only by the proper deployment of technical, institutional, and political countermeasures to make the benefits of an expansion of nuclear power outweigh the risks.

14.6 Questions for discussion

1. Which nuclear materials used or produced in a nuclear energy program might be used for nuclear weapons? Which materials properties make these materials attractive or render them unattractive for nuclear-weapon use. Explain the production mechanisms and the civil or possible military use of these materials.
2. Discuss the extent to which benefits of nuclear power with regard to proliferation might be outweighed by proliferation risks. How does the analysis change if nuclear power expands in the future?
3. Explain the threats that the use or production of weapon-usable nuclear materials can pose for international security.
4. Which choice of nuclear fuel-cycle facilities was most important for the capability to produce fissile materials in the cases of North Korea and Iran?
5. Which countries possess large civilian stockpiles of fissile materials? How and why was this material produced?
6. What technical or political and institutional mechanisms are proposed to reduce the risk of proliferation? How can the proliferation risks be managed?
7. In what regard can materials science research contribute to address proliferation risks?
8. Try to explain, analyze, and discuss the complex interaction of science, technology, and society that is typical for our modern world (climate, biotechnology, cyberspace), taking nuclear energy and proliferation as examples.

14.7 Further reading

- A comprehensive treatment of all aspects of the use of nuclear energy, especially with chapters on nuclear proliferation, is given in **D. Bodanski**, 2004, *Nuclear Energy: Principles, Practices, and Prospects*, 2nd edn., New York, Springer-Verlag, 2004.
- The standard textbook for processes developed to concentrate, purify, separate, and safely store fissile materials is **M. Benedict**, **T. H. Pigford**, and **H. W. Levi**, 1981, *Nuclear Chemical Engineering*, 2nd edn., New York, McGraw Hill.
- A comprehensive assessment on proliferation dangers and policies to control them, with data on countries that have or have given up nuclear weapons, is given in **J. Cirincione**, **J. B. Wolfsthal**, and **M. Rajkumar**, 2005, *Deadly Arsenals, Nuclear, Biological, and Chemical Threats*, 2nd edn., Washington, DC, Carnegie Endowment for International Peace.
- A comprehensive treatment of cutting-edge technologies used to trace, track, and safeguard nuclear material is available in **J. E. Doyle** (ed.), 2008, *Nuclear Safeguards, Security, and Non-proliferation: Achieving Security with Technology and Policy*, Burlington, MA, Butterworth-Heinemann.
- This book, which is fairly technical but understandable for nonscientists, gives an overview of how nuclear weapons explode and how nuclear reactors operate, and presents options on treating nuclear waste: **R. L. Garwin** and **G. Charpak**, 2001, *Megawatts and Megatons: A Turning Point in the Nuclear Age*, New York, Knopf.
- A discussion between two of the most well-known scholars on international relations concerning whether more or fewer nuclear weapons would

be better: **S. Sagan** and **K. Waltz**, 2002, *The Spread of Nuclear Weapons, A Debate Renewed*, New York, W. W. Norton & Company.

- This comprehensive overview provides information about both the basic technologies and the international efforts to prevent the spread of nuclear weapons and sensitive technologies: **R. F. Mozley**, 1998, *The Politics and Technology of Nuclear Proliferation*, Washington, DC, University of Washington Press.
- This comprehensive study discusses the interrelated technical, economic, environmental, and political challenges facing a significant increase in global utilization of nuclear power: **MIT**, 2003, *The Future of Nuclear Power* Washington, DC, MIT (updated 2009), http://web.mit.edu/nuclearpower/.
- This comprehensive overview on uranium enrichment technology and its relevance for proliferation is still a must read in the field: **A. Krass**, **P. Boskma**, **B. Elzen**, and **W. A. Smit**, 1982, *Uranium Enrichment and Nuclear Weapon Proliferation*, Basingstoke, Taylor & Francis.
- Although the world inventories have changed, this book provides timeless insights and methods that are extremely useful for the assessment of inventories of fissile materials: **D. Albright**, **F. Berkhout**, and **W. Walker**, 1997, *Plutonium and Highly Enriched Uranium 1996. World Inventories, Capabilities and Policies*, Oxford, Oxford University Press.
- A collection of articles by world-leading scholars addressing the challenges of the use of nuclear power with several articles on various aspects of the interlinkage of nuclear power and proliferation is available in **S. E. Miller** and **S. D. Sagan** (eds.), 2009, *The Global Nuclear Future, Daedalus*, **138**(1:4), 1–167 S. E. Miller and S. D. Sagan, (eds.), 2010, *The Global Nuclear Future. Daedalus*, **139** (2:1), 1–140.
- The most comprehensive source of background and reference material on the Nuclear Non-proliferation Treaty and its associated regime is **J. Simpson**, **J. Nielsen**, and **M. Swinerd**, 2010, *The NPT Briefing Book*, Southampton, The Mountbatten Centre for International Studies.
- A bibliography of arms-control literature is available in **A. Glaser** and **Z. Mian**, 2008, "Resource letter PSNAC-1. Physics and society. Nuclear arms control," *Am. J. Phys.*, **76**(1), 5–14.

14.8 Appendix: Emerging or aspiring nuclear-weapon states

Twelve countries have developed or acquired nuclear weapons since the beginning of the atomic age [46]. All states that have built nuclear weapons appeared to have placed the need for nuclear weapons before the desire for commercial nuclear power, although India appears to have developed both, concurrently. Several other countries had active nuclear-weapon programs, but abandoned them before building such weapons.

Although commercial nuclear power played no direct role in any of these cases, most of them have links to the potential pathways described in Section 14.3. The list is not comprehensive and readers should refer to Cirincione *et al.* [6] for more details.

14.8.1 India

India used research facilities, which had been built ostensibly for civilian use with foreign assistance (e.g., the CIRUS reactor), to produce weapons-grade plutonium for its "peaceful" nuclear test in 1974. After a long hiatus, India conducted five nuclear tests in two days in 1998 and declared itself a nuclear power. India used its reprocessing plants in Kalpakkam and Tarapur for military and civilian purposes.

14.8.2 Pakistan

Pakistan used centrifuge blueprints, stolen from URENCO in Belgium by A. Q. Khan in 1976, and developed a wide web of nuclear suppliers, building a clandestine HEU weapon capability, which it demonstrated with six nuclear tests in response to India's tests in 1998 [46].

14.8.3 North Korea

North Korea used the Soviet Atoms for Peace assistance to train its nuclear scientists and establish nuclear research facilities, which was followed by building indigenous facilities for the full plutonium fuel cycle under the guise of a civilian program, after having signed the NPT. It eventually withdrew from the NPT and tested nuclear weapons in 2006 and 2009 [46]. In 2010, it also unveiled a modern, small industrial-scale centrifuge enrichment facility.

14.8.4 Iran

Iran used the A. Q. Khan network and its own worldwide procurement network to develop clandestine uranium centrifuge facilities. Once these facilities were discovered in 2002, Iran put in place all the capabilities to produce weapons-grade material by building enrichment facilities ostensibly for commercial use, claiming the right to peaceful nuclear energy under Article IV of the NPT. Combined with prior work on weaponization [46], Iran is believed to possess the latent-nuclear-weapon option, which it could exercise quickly if it chose to do so, albeit requiring abrogation of IAEA safeguards and its withdrawal from the NPT. Iran will also be capable of producing weapons-grade plutonium at the level of nearly two bombs per year with its heavy-water research reactor under construction in Arak.

14.8.5 Syria

It is suspected that North Korea provided Syria with a plutonium production reactor, which was destroyed by an Israeli air strike in 2007 [46]. Although it was built on Syrian soil, it remains unclear who the customer was for the plutonium that was to be produced by this reactor.

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