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From Nuclear Energy to the Bomb: The Proliferation Potential of New Nuclear Energy Programs

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Addressing International Governance Challenges

Summary

This paper explores the connection between otherwise peaceful nuclear energy programs and nuclear weapons with the objective of clarifying their relationship. Specific attention is paid to the technical aspects of proliferation, particularly regarding scientific knowledge and expertise, nuclear material, technology and infrastructure.

Main findings are:

- Nuclear energy and weapons are inextricably linked by the scientific principles that underscore both, but beyond this basic understandingthe intricacies of the technical relationship between the two are complex.
- A once-through nuclear program provides a basic foundation in nuclear science and reactor engineering for a nuclear weapons program, but does not provide knowledge of sensitive fuel cycle technology or bomb design and assembly.
- A peaceful nuclear energy program does, however, provide a state with much of the expertise, personnel, infrastructure and camouflage it would need to begin work on a weapons program should it chose to do so.
- Acquiring a peaceful nuclear energy infrastructure does enhance a state's capacity to develop nuclear weapons, but capacity is only one consideration and of secondary importance to other factors that drive state motivations for the bomb.

Canadian Centre for Treaty Compliance

CIGI's Nuclear Energy Futures Project is being conducted in partnership with the Centre for Treaty Compliance at the Norman Paterson School of International Affairs, Carleton University, Ottawa.

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Letter from the Executive Director

On behalf of The Centre for International Governance Innovation (CIGI), it is my pleasure to introduce the Nuclear Energy Futures Papers Series. CIGI is a non-partisan think tank that addresses international governance challenges and provides informed advice to decision makers on multilateral governance issues. CIGI supports research initiatives by recognized experts and promising academics; forms networks that link world-class minds across disciplines; informs and shapes dialogue among scholars, opinion leaders, key policy makers and the concerned public; and builds capacity by supporting excellence in policy-related scholarship.

CIGI's Nuclear Energy Futures Project is chaired by CIGI distinguished fellow Louise Fréchette and directed by CIGI Senior Fellow Trevor Findlay, Director of the Canadian Centre for Treaty Compliance at the Norman Paterson School of International Affairs, Carleton University, Ottawa. The project is researching the scope of the purported nuclear energy revival around the globe over the coming two decades and its implications for nuclear safety, security and nonproliferation. A major report to be published in 2009 will advance recommendations for strengthening global governance in the nuclear field for consideration by Canada and the international community. This series of papers presents research commissioned by the project from experts in nuclear energy or nuclear global governance. The resulting research will be used as intellectual ballast for the project report.

We encourage your analysis and commentary and welcome your thoughts. Please visit us online at www.cigionline.org to learn more about the Nuclear Energy Futures Project and CIGI's other research programs.

John English
Executive Director

Introduction

This paper considers the scientific and institutional capability that a peaceful nuclear energy program may or may not provide to a non-nuclear weapon state that wishes to develop a nuclear explosive device.[1] Renewed interest in nuclear energy in dozens of states without a current nuclear energy program raises the potential for a diffusion of nuclear technology around the globe. The proliferation of peaceful nuclear energy capacities to new states, many would argue, goes hand in hand with the spread of latent capacities for developing nuclear explosive devices,[2] due to the crossover of scientific knowledge and technologies. This paper asserts that while a peaceful nuclear program provides a state with much of the technology, knowledge, expertise and infrastructure required to obtain fissile material for a nuclear device, it does not provide a state with sufficient expertise or the technology necessary to design and assemble one. A peaceful nuclear program can put a country on the path to the technical competence necessary to construct a nuclear device, but it does not remove all obstacles to acquiring fissile material, nor does it provide the capability to weaponize and deliver a device.[3]

For the purposes of this paper, a peaceful nuclear energy program is defined as one in which a state is responsible for operating at least one current generation power reactor. As such, it excludes the potential proliferation resistance of next generation reactors, as well as turnkey operations in which the buying state does not have a major role in the design or construction of the reactor (although it may ultimately have a role in operating the reactor). This paper assumes that all new power reactors built in non-nuclear weapon states will be subject to International Atomic Energy Agency (IAEA) safeguards, although it does not assess how difficult it would be for a state to circumvent safeguards to divert nuclear material.

This paper will first determine what can be learned from a "once-through" nuclear program that could help build a nuclear device. A once-through nuclear program uses natural uranium or low-enriched uranium (LEU) only once in a power reactor, thereby precluding any reprocessing. This type of program is typical of most state nuclear programs and is unlikely to change with future new entrants, due in part to the web of unilateral, bilateral and multilateral technology transfer restrictions[4] designed to prevent the emergence of new enrichment and reprocessing states.[5] These once-through nuclear energy programs are expected to comprise the bulk of new nuclear build in the coming decades as a part of the purported nuclear revival.

Next, the paper specifies what enrichment or reprocessing technology can add to a state's ability to build a nuclear device. Enrichment or reprocessing is required to produce the material for a nuclear device, so these technologies constitute an important step towards a state acquiring the technical capability to do so.

Finally, this paper outlines what is required for a state to make the leap from nuclear energy to a nuclear device.

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[2] For the purposes of this paper a nuclear device refers specifically to a nuclear explosive device, and not other peaceful nuclear devices such as cancer therapy machines, food irradiators, smoke detectors, and so forth.

[3] For the purposes of this paper, the ability of a state to detonate a nuclear device will be considered the point of concern for technical proliferation. Weaponization will not be addressed, although it is a challenging necessary step for a state trying to obtain a fully deliverable nuclear arsenal. For more information about the challenges of weaponization see Nuclear Threat Initiative (2009).

[4] For example, the Nuclear Suppliers Group, nuclear safeguards agreements and bilateral nuclear cooperation agreements.

[5] There are some exceptions. Brazil has recently started enrichment, while Argentina, South Africa and South Korea are exploring pyroprocessing, a form of reprocessing, though these are far from established programs. Argentina is also pursuing its own gaseous diffusion enrichment capability.

Author Biography

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Once-through Fuel Cycle

A once-through fuel cycle typically involves a nuclear power reactor fuelled by LEU, storing the spent fuel as waste after its first use.[6] LEU in these cases is supplied by a select few advanced nuclear states with enrichment capabilities. The major nonproliferation benefit of a once-through fuel cycle is that the operating state does not come into direct contact with weapons grade material – high-enriched uranium (HEU) or plutonium – or the technology to acquire it at any stage. The technical proliferation involved in a once-through fuel cycle is discussed below.

Scientific Expertise and Fissile Material

The connection between nuclear energy and weapons is one that is typically characterized by the dual role of fissile material. Both nuclear reactors and nuclear bombs use either uranium or plutonium to create a nuclear chain reaction that releases energy. The speed with which they release energy is the crucial difference between the two: in a reactor the energy release is controlled and sustained over an extended period, whereas in a nuclear bomb the release occurs in fractions of a second. The science of fission is fairly straightforward; however, controlling fission reactions to get the desired effect is challenging. A fission reaction is induced by introducing neutrons into certain isotopes of uranium or plutonium atoms,[7] thereby causing them to become unstable and split into lighter atoms. These lighter atoms do not equal the mass of the initial atom, and in the process this lost mass is converted into energy, as per Albert Einstein's famous $E=mc^2$ formula.[8] Nuclear reactors and explosives both harness the energy produced by fission, but this basic understanding does little to reveal the relationship between the two.

The scientific knowledge and engineering prowess required for a nuclear reactor and a nuclear device are only somewhat interchangeable. To develop a nuclear device, the difference in the speed of the chain reaction creates additional requirements for the firing mechanism, grade of the uranium or plutonium used, and the density, physical surrounding and shape of the fissile material.[9] These differences are substantial barriers to a state looking to shift from power production to assembling a nuclear device. Controlling the flow of neutrons in a power reactor arguably requires more sophisticated technology than a basic nuclear weapon, but the technologies are essentially different and require a different set of knowledge and expertise (Mozley, 1998: 23-25, 44-46). There are, however, certainly benefits to be had in terms of knowledge and expertise in operating a power reactor that make state acquisition of a nuclear device easier.

There is considerable crossover between peaceful and military disciplines of scientific study in the nuclear field. The majority of these disciplines are specific to design and operation of a nuclear reactor or to enrichment and reprocessing techniques. Scientific disciplines in which this crossover exists include:

- Nuclear engineering
- Chemical engineering
- Metallurgical engineering
- Mechanical engineering
- Electrical engineering
- Physics
- Mathematics and computer science
- Chemistry

Calculating fissile atom depletion and production, criticality calculations, and the design of nuclear reactors are some examples[10] of peaceful-military crossover in nuclear engineering (Comptroller General of the United States, 1979). There is substantial overlap between civilian and military nuclear applications, but little useful for learning how to design and assemble a nuclear device. Some of this overlap – particularly chemical engineering – is specific to sensitive fuel cycle technologies and an understanding of these areas is not typical of most nuclear energy programs. Nonetheless, a peaceful program provides the scientific foundation upon which a state can go on to build and operate its own dedicated plutonium production reactor to produce the material for a nuclear weapon. A dedicated reactor is ideal for a weapons program using plutonium because of the challenges associated with

6 The vast majority of reactors are light water reactors (LWR) that use LEU. There are a small number of heavy water reactors that use natural uranium as fuel. They are able to use natural uranium because heavy water has a low affinity for neutrons, thus increasing the availability of neutrons for fission reactions.

7 U-235, U-233 and Pu-239 all become unstable when a neutron is introduced. Natural uranium contains 99.284% U-238, 0.0058% U-234 and only 0.711% of the fissionable U-235, hence the need for enrichment technology to increase the level of U-235. Plutonium does not occur in nature, hence the need for reprocessing. See Mozley (1998: 21-42).

8 Einstein's formula gives the fundamental relationship between mass and energy. In prose, energy (E) is equal to the square of the product of mass (m) and the speed of light (a constant 'c').

9 For information on the "cross section" of a nuclear chain reaction see Mozley (1998: 32-36).

10 See Appendix A for a detailed list.

using reactor grade material for a nuclear device and the difficulty of circumventing IAEA safeguards designed to prevent the diversion of material and facilities from peaceful to military purposes.[11]

Neither LEU feedstock nor the plutonium contained in the spent fuel from a power reactor is ideal for building a first nuclear weapon.[12] To fully illustrate that point, there has never been an instance of a state diverting power reactor-grade material (uranium or plutonium) to use in a nuclear device. Using reactor grade material in a nuclear device is possible in some cases (Gilinsky, 2004), but the technological sophistication involved limits this possibility to the most advanced states. Ideally, uranium needs to be enriched to 90 percent or higher U-235 to be considered weapons grade, compared with the 3 to 5 percent used in most light-water reactors (LWRs).[13] With low enrichment levels the amount of material needed for the device to reach criticality is high enough that the device could not realistically be detonated, particularly at enrichment levels below 20 percent (International Panel on Fissile Materials, 2007). Nuclear devices using material with lower enrichment levels have been built by advanced weapons laboratories,[14] but even in these cases the enrichment level is more in the realm of 20 percent rather than 3 to 5 percent. A non-nuclear weapon state is unlikely to be able to accomplish such a difficult technical feat.

Reprocessed spent power reactor fuel, regardless of the type of feedstock, is not an ideal source of plutonium for a nuclear device due to the high occurrence of Pu-240, an isotope of plutonium that has a high rate of spontaneous fission. Pu-239 is the desirable isotope of plutonium for a controlled fission process and its occurrence is highest when the fuel is left in the reactor for a relatively short time. The longer the initial fuel is left in the reactor the higher the occurrence of Pu-240, as is the case with power reactor fuel. Given the longer time that power reactor fuel stays in the reactor the Pu-240 build-up is high. It is, however, possible to use reprocessed power reactor fuel high in Pu-240 for an implosion device. Despite long-held beliefs to the contrary, the US National Academy of Sciences and US Department of Energy (DOE) reached this conclusion in the 1990s:

> "Virtually any combination of plutonium isotopes… can be used to make a nuclear weapon. In short, reactor-grade plutonium is weapons-usable, whether by unsophisticated proliferators or by advanced nuclear weapons states." (Feiveson, 2004)

Plutonium from any reactor does pose a diversion risk, but states are more likely to attempt to build a clandestine dedicated production reactor to circumvent safeguards rather than attempt diversion from a power reactor. Reprocessed plutonium is not typically used as reactor fuel[15] for economic reasons but there are initiatives to change this such as mixed-oxide (MOX)-fuelled or fast breeder reactors.[16] Furthermore, it is unlikely that a state would attempt to acquire material for a nuclear device by diverting power reactor grade material rather than using a dedicated plutonium production reactor because of the potential for spontaneous fission problems.

Operating a power reactor does not provide a state with access to weapons material on the front or back end without an enrichment or reprocessing facility, and in the case of a plutonium device, without the additional task of building a plutonium production reactor or diverting material from a power reactor. The ease with which a state can convert a power reactor is dependent on its type (Gilinsky, 2004: 24-31). A LWR can be used to produce the desirable Pu-239 simply by reducing the length of time the fuel spends in the core; however, the amount of fuel required to do so is staggering and a clear signal that a state is using the reactor to produce plutonium if the facility is under safeguards. The same is true of a commercial heavy water reactor (HWR). The perceived main benefit of using a HWR to produce plutonium is that it does not need to be shut down to refuel. This perception is inaccurate, however, since a current HWR cannot be refueled fast enough to function as a production reactor. Misusing power reactors to produce plutonium is not technically

[11] All new power reactors that are not located in the five official or four unofficial nuclear weapon states (including North Korea) are required to be under safeguards. A state can, of course, build a clandestine reactor, but in this case the state is almost assuredly going to build a dedicated production reactor and not a power reactor for pragmatic reasons.

[12] Weapons grade material can be used as reactor fuel, but there is no incentive to do so. The exceptions to this are global initiatives such as the Global Partnership Program (GNEP) to reduce stockpiles of weapons grade plutonium by burning the material in power reactors, particularly stockpiles remaining in the former Soviet Union.

[13] Uranium weapons can be made using 20 to 90 percent enriched uranium, but the complexity and practicality of doing so drops dramatically with the enrichment level. The bomb dropped on Hiroshima in 1945 consisted of 80 percent enriched uranium.

[14] It is also difficult to predict the yield of a device with lower enrichment levels but this may not be much of a concern to a state pursuing one.

[15] Every reactor in operation today derives between a third and a half of its energy output from plutonium that is produced in-situ during normal operation.

[16] Mixed-oxide fuel (MOX) blends plutonium with uranium and is an exception. Only a few advanced nuclear countries have produced MOX and the economics of it are questionable, so it is not widely distributed. MOX is not weapons ready material but according to the IAEA isolating the plutonium is fairly simple.

difficult, but a state would need to circumvent IAEA safeguards to do so, raising alarm bells immediately. A misused power reactor would also be far less efficient than a dedicated production reactor. Although power reactors can theoretically be misused to produce weapons material, in most cases a state would be better off acquiring a dedicated plutonium production reactor in order to circumvent safeguards and improve material production efficiency.

Another benefit of a once-through nuclear program is learning how to handle radioactive material. Nuclear power reactors produce a large amount of highly radioactive material because of the time the nuclear material spends in the reactor. The longer the material stays in the reactor the greater the concentration of highly radioactive fission products and transuranic elements (Nuclear Energy Policy Study Group, 1977: 246). The radioactivity of the material is several magnitudes higher than that of material produced in a dedicated plutonium production or research reactor. All of the techniques involved in handling radioactive material from a dedicated plutonium production reactor can thus be learned by operating a power reactor, at least up until the reprocessing stage (Mozley, 1998: 56-63). However, since the uranium enrichment path to a nuclear device requires little exposure to radiation this might be the preferred option. Techniques for handling radiation can be useful in the plutonium path to the bomb,[17] but the major challenges posed by radiation can be bypassed entirely by enriching uranium instead.

Infrastructure and Personnel

The main benefit derived from a once-through nuclear energy program for the construction of a nuclear device is the buildup of nuclear infrastructure that would otherwise be difficult, if not impossible, to camouflage. States have used technical assistance and training provided by advanced nuclear states and the IAEA – justified on the basis of their nuclear power generation needs – to enhance their potential nuclear weapons capability.[18] India, Israel, North Korea, Pakistan and South Africa all used some degree of peaceful assistance from advanced nuclear states in their eventual weapons programs. The Nuclear Suppliers Group (NSG) has established a list of equipment and components that can be used for peaceful or weapons purposes. Export of these items is controlled by the NSG, but the size of the list reveals that much of the equipment and components a state needs to produce a weapon can be acquired under the guise of peaceful applications.

There is no empirical way to determine the importance of a peaceful nuclear energy program to eventual weapons development, but evidence suggests that it is critical, particularly in developing states that lack adequate institutions for higher learning. In a conversation with George Perkovich, Munir Ahmen Kahn, former leader of Pakistan's nuclear program, said:

> "The Pakistani education system is so poor, I have no place from which to draw talented scientists and engineers to work in our nuclear establishment. We don't have a training system for the kind of cadres we need. But, if we can get France or somebody else to come and create a broad nuclear infrastructure, and build these plants and these laboratories, I will train hundreds of my people in ways that otherwise they would never be able to be trained. And with that training, and with the blueprints and the other things we'd get along the way, then we could set up separate plants that would not be under safeguards, that would not be built with direct foreign assistance, but I would now have the people who could do that. If I don't get the cooperation, I can't train the people to run a weapons program." (Perkovich, 2002: 194)

Pakistan was highly dependent on outside knowledge and assistance while building a nuclear device. India, likewise, received training and technology from the US and Canada, including a research reactor that was used to produce the material for India's 1974 nuclear test. France supported Israel's nuclear program by providing technology and equipment during the 1950s, leading to the eventual development of the Israeli nuclear bomb.[19] Further, North Korea received assistance from the Soviet Union, which included a research reactor, and was later supplied clandestinely by Pakistan which led to its eventual detonation of a nuclear device in 2006. In addition, South Africa received a research reactor and the high-enriched uranium required to fuel it from the United States, an act viewed as the genesis of its nuclear program.[20] Every case of successful nuclear weapons development since the 1968 Nuclear Non-Proliferation Treaty (NPT)

[17] Although the basic techniques remain the same, there are added challenges in handling the radioactivity involved in acquiring plutonium. A more detailed assessment of these challenges will be included in the next section.

[18] See Appendix B for a list of dual use technologies.

[19] In Israel's case it did not bother to continue with its peaceful nuclear energy program and diverted all of its resources to weapons development.

[20] For detailed historical accounts of nuclear assistance to India, Israel, North Korea, Pakistan and South Africa see the *Nuclear Threat Initiative's* country profiles. Available at: http://www.nti.org/e_research/profiles/index.html.

came into effect in 1970 occurred under the guise of a peaceful nuclear program with the assistance of nuclear supplier states.

Most transfers of nuclear technology, however, do not involve sensitive fuel cycle technology. Importing reactors and the knowledge to build and operate them is not sufficient for a state to move into weapons development. The state must acquire an independent enrichment or reprocessing capability, or obtain weapons grade fissile material from another source. Pakistan, Israel and North Korea all had the benefit of assistance with sensitive fuel cycle technologies from a nuclear supplier.[21] India, on the other hand, used nuclear technology and expertise gained from American and Canadian assistance prior to 1974 to autonomously develop a reprocessing capability.[22] The Indian and South African cases demonstrate that even without direct assistance with enrichment or reprocessing technology, a state can use an otherwise peaceful nuclear infrastructure to simplify its path towards a nuclear device. The scientific knowledge, expertise and infrastructure required for a peaceful nuclear energy program can provide an opportunity for a state to develop enrichment and reprocessing technologies. In the context of latent proliferation, a peaceful nuclear energy program is best characterized as a stepping stone to acquiring the wherewithal for a nuclear device.

Training foreign scientists in nuclear engineering and related fields may in some cases pose proliferation risks, but advanced nuclear states have undertaken to provide it, either voluntarily or in accordance with international agreements. Bilateral assistance efforts, beginning with the US ”Atoms for Peace" program in the 1950s, the statute of the IAEA, and Article IV[23] of the NPT have all encouraged the global spread of nuclear expertise for peaceful purposes. Both the IAEA and member states provide training seminars, workshops and other technical assistance to states that request it.[24] Training in sensitive fuel cycle technologies has declined since the 1960s as a result of proliferation concerns,[25] but nuclear training continues nonetheless. A declassified report by the Comptroller General of the United States characterizes the problem with limiting training programs to avoid providing sensitive nuclear expertise:

> “Department of Energy officials said that sensitive areas of nuclear technology have been examined and precautions have been taken, but it is difficult to draw a firm line between what is and is not sensitive; it is a matter of degree.” (Comptroller General of the United States, 1979: vi)

Training programs provided by the IAEA and member states educate foreign scientists in fields that are necessary – though not sufficient – to understand the design and construction of a nuclear device or replicate sensitive technologies such as enrichment or reprocessing. While these training programs can and have contributed to proliferation, the pertinent question is the motivation and intention of the scientists being trained. Newly trained nuclear scientists and engineers are the largest proliferation concern arising from a peaceful nuclear energy program because they have the capability to expand their activities to include more sensitive, weapons applications.

Sensitive Fuel Cycle Technology

Enrichment and reprocessing plants are considered sensitive because a state with access to either can produce weapons grade material for a nuclear device. Enrichment and reprocessing technology may be used to produce fissile material for a power reactor or a device, but there are differences, albeit mostly inconsequential differences, in how the technology is used to do so. The acquisition of enrichment or reprocessing technology marks a leap forward for a state intent on developing a nuclear device.

Enrichment

Almost all power reactors use LEU as fuel. Exceptions to this include a small number of reactors manufactured by Canada and India that are moderated by heavy water and use natural uranium as fuel, and old British gas-graphite

[21] Pakistan had help from France in building the Chasma and Pinstech reprocessing plants, China is suspected of helping Pakistan with the Kahuta enrichment plant. France also assisted Israel to construct the Dimona reprocessing plant. North Korea received reprocessing technology from the Soviet Union in the 1960s, and is suspected of receiving designs and components for an enrichment plant supplied by Pakistan. For further details see Kroenig (2009) and “North Korea Profile – Nuclear,” (2009).

[22] For more information on India’s nuclear program see Perkovich (1999).

[23] Article VI states that “Each of the Parties to the Treaty undertakes to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a treaty on general and complete disarmament under strict and effective international control.”

[24] At least two dozen states provide various degrees of nuclear training. See Comptroller General of the United States (1979).

[25] For example, during the 1960s and 1970s, the US government allowed a few dozen foreign scientists to be involved in unclassified research relating to enrichment or reprocessing. See Comptroller General of the United States (1979: i).

reactors.[26] There are relatively few non-nuclear weapon states with a domestic enrichment capability, and among them only Iran is currently considered at risk of using it for weapons purposes.[27] States with nuclear reactors that do not enrich domestically import LEU from a major supplier, often France, Russia, the US or URENCO, which is jointly owned by Germany, the Netherlands and the UK. There has been a G8 moratorium on exporting enrichment (and reprocessing) technology to new states since 2004, but the group chose not to extend it early in 2009. Instead, it has encouraged its members to avoid transferring certain technologies in a way that would enable their reproduction. The United States is working through the NSG to establish strict criteria for such transfers (Pomper and Boese, 2008). The likelihood of new enrichment states emerging in the short-term is relatively low and yet, as long as power reactors use enriched fuel and states are legally permitted to have the full nuclear fuel cycle, it will be the sovereign right of states to enrich uranium should they choose to. Therefore, the possibility of new enrichment states persists.

A state with an enrichment facility can produce HEU for a nuclear device.[28] The difference between producing LEU and HEU is the number of times the material is put through the centrifuges in "batch" enrichment. Otherwise, the centrifuges can be reconfigured for HEU production.[29] Roughly two-thirds of the enrichment required to produce HEU is already done if a state begins the process with LEU.[30] Thus, the volume of material required is significantly less if a state has access to LEU. The difference in starting the enrichment process with LEU rather than natural uranium is more a matter of time than ability. In terms of scientific and technical capability, the kind of material a state starts the enrichment process with is a moot point. Once a state has an enrichment facility it is capable of producing weapons grade material.

Obtaining enrichment technology generally requires the assistance of a nuclear supplier. Enrichment technologies are closely controlled by the countries that own them, so an aspiring enrichment state would need to make a compelling case to a supplier state and the Nuclear Suppliers Group to obtain them. The alternative of acquiring designs and equipment through clandestine networks may no longer be an option since the uncovering of the AQ Khan network in 2003.[31] It is also possible for a state to develop an indigenous capability over time – as Argentina, Brazil and South Africa have – though it would still be dependent on its scientists receiving the necessary training and expertise. The size and electric power requirements of enrichment facilities are large enough that it would be difficult to clandestinely develop them, even with illicit assistance, although modern facilities are smaller and increasingly difficult to detect.[32] The proliferation risk with enrichment facilities is closely intertwined with the willingness of current enrichment states to provide necessary design information as well as access to certain parts and equipment. As a result, the emphasis of the nonproliferation regime has been on limiting the supply of enrichment technology. These supply limitations are a large part of the difficulty a newcomer state faces if attempting to enrich its own uranium for a nuclear device.

Reprocessing

Reprocessing spent reactor fuel (or waste) to produce plutonium is not generally considered an economically viable way to obtain fuel for civilian power reactors, but has historically been the path of choice for states seeking a nuclear device. Despite being more difficult to design than a uranium device, the first nuclear tests conducted by the US, the Soviet Union, the UK, France, India and North Korea all used plutonium from a dedicated production or research reactor, and Israel's untested arsenal is presumed to be of plutonium weapons as well.[33] Only

[26] The abundance of neutrons in heavy water allows for the use of natural uranium because it reduces the neutron generation required by the fission process itself, thereby circumventing the requirement for higher U-235 levels in most reactors. The biggest downside of heavy water moderated reactors is economic: heavy water is expensive to produce and the initial capital outlay of these plants is relatively high.

[27] China, France, India, North Korea, Pakistan, Russia, UK and US have enrichment plants as well as nuclear weapons. Brazil, Germany, Japan, Iran and the Netherlands have enrichment plants, and aside from Iran, have long chosen to forego acquiring their own nuclear weapons.

[28] Although enrichment can also be done through gaseous diffusion, chemically, electromagnetically or with lasers, centrifuge technology is the most cost effective and most common technology used today. Some advanced nuclear states are exploring alternative enrichment technologies. See NTI (2009).

[29] Batch recycling or reconfiguring the centrifuges for HEU production are not prohibitively difficult for a state already successfully operating them. See Albright and Shire (2007).

[30] Although the gap between 3 and 90 percent enriched uranium sounds large, a substantially larger amount of natural uranium would be required to produce HEU than if a state were starting the process with LEU. See Mozley (1998: 77-125).

[31] The technology is closely controlled enough that even a champion of nonproliferation like Canada was unable to persuade the US to provide it with enrichment technology that was not black-boxed. The NSG is in the process of determining criteria for such transfers. See Pomper (2008).

[32] For more information about the difficulty in concealing and powering enrichment facilities, see Mozley (1998: 124-125).

[33] The US assembled a uranium device before a plutonium one, but Manhattan Project scientists were so confident in their uranium weapon that they decided not to test it before deploying one over Hiroshima. Thus, while the US example is technically accurate, it fails to make the point. See Mozley (1998: 43).

China and Pakistan detonated a uranium weapon first, and South Africa's untested weapons were also of uranium. The plutonium isotope Pu-240 produces a massive amount of neutrons when it undergoes spontaneous fission, inevitably causing a poorly designed nuclear device to detonate prematurely or "fizzle" (Bernstein, 2008: 139-140). This creates challenges in design that would seemingly lead to the conclusion that a uranium device would be easier for states to pursue first. Pakistan, in fact, gave up trying to design a plutonium device because it was too complicated. Despite these added challenges, states have historically chosen the plutonium path to the bomb because reprocessing technology is simpler to master than enrichment technology.

For a determined state, reprocessing is difficult though not prohibitively so. For an emerging nuclear country, the challenge of reprocessing technology is not the chemical separation process but handling the highly radioactive byproducts of reactor operation and plutonium separation (Mozley, 1998: 56-63). A reprocessing plant needs to handle millions of curies of fission products in the form of highly concentrated solutions and vapours (Krishnamony et al., 1969: 253). The "availability"[34] of radiation in these solutions and vapours is substantially higher than that of once-through reactor fuel. Whereas in a power reactor the highly radioactive fission products are contained within the fuel element, in a reprocessing plant they are extracted and need to be handled directly (Krishnamony et al., 1969: 253). A state without an existing commercial reprocessing capability would need to acquire or develop the technology and techniques to handle the additional radiation challenges if it wanted to use plutonium for a bomb.

Any conventional reprocessing facility can extract plutonium for civilian or military use. The difference in the chemical composition of byproducts that result from reprocessing spent fuel from a power reactor versus a production reactor is negligible in terms of the handling and storage techniques required (Krishnamony et al., 1969: 250-252). France, for example, stores most of its military and civilian reprocessing byproducts in the same locations, and they are handled identically by the same company (Davis, 1988). Reprocessing spent fuel creates a number of waste streams that a state would not encounter in a once-through power program, leading to a higher volume of waste and a much "hotter" or higher density level of radioactivity (Vandenbosch and Vandenbosch, 2007: 15-21). These are all significant challenges to safely operating a reprocessing facility. The more important consideration is how concerned a state clandestinely pursuing nuclear weapons would be about protecting workers, the public and the environment from the hazards of reprocessing byproducts. Given that the greatest challenges in handling radioactivity resulting from reprocessing occur only after the plutonium has been extracted, radioactive waste is a moot point. A more significant challenge pertaining to waste may be avoiding detection from increasingly effective wide-area sampling techniques employed by the IAEA or other interested parties.

Handling reprocessing radioactivity is significantly easier when a dedicated production reactor is used to produce plutonium. According to the DOE, reprocessing spent power reactor fuel involves handling about 25 times the amount of radioactivity as handling the spent fuel from a dedicated weapons production reactor (Alvarez, 2008). The implication is that a state with a nuclear energy program involving a reprocessing capability is overqualified to handle radioactivity in reprocessing weapons grade material.

Politics of Proliferation

India and South Africa were able to develop indigenous reprocessing and enrichment capabilities with minimal outside help, meaning little direct transfer of sensitive fuel cycle technology designs or equipment. Both states were, however, operating within an international climate in which they had several advantages over states at similar stages of development today. They were among the main beneficiaries of development initiatives that encouraged technical assistance and foreign aid, including a wide range of nuclear technologies (Pilat, 2007). Until India's nuclear test in 1974, advanced nuclear states were somewhat lax about restricting access to training and assistance in sensitive areas of nuclear technology, including enrichment and reprocessing (Comptroller General of the United States, 1979). Indian and South African scientists had access to more outside training and expertise than their contemporary counterparts. Furthermore, nuclear export controls and safeguards were still rudimentary in the 1960s and 1970s, so it would have been easier to obtain equipment and components and to build facilities without attracting international attention. Advanced nuclear states and the nonproliferation regime have learnt from past mistakes. The relative ease with which

[34] Radiation availability refers to the degree to which radioactive elements are exposed to their external environments. In the case of nuclear energy, radiation is less available when contained in the spent fuel element.

Indian and South African scientists indigenously developed sensitive fuel cycle technology is not likely to be replicated anytime soon.[35]

Today, sensitive fuel cycle technology is difficult for states to obtain for political reasons. The proliferation risks associated with it are now well known, so nuclear suppliers have taken steps to limit its dissemination. The NSG, established in 1974, is working towards strict criteria for new enrichment or reprocessing states that should limit their emergence.[36] There are also several ongoing initiatives to discourage states from wanting either technology, including but not limited to the IAEA's multilateral fuel bank initiative and the joint Russian-Kazakh Angarsk enrichment facility.[37] The global nonproliferation regime is trying to close the gap in the NPT whereby a state can acquire much of the technology and expertise it needs for a weapons program, especially sensitive fuel cycle technology, and then withdraw from the treaty to pursue a nuclear device. The regime is targeting enrichment and reprocessing technology since without one of these technologies states cannot produce the material for a nuclear weapon.

Pakistani scientist Abdul Qadeer Khan was able to circumvent nonproliferation measures, eventually setting up a black market for nuclear blueprints, equipment and materials. Khan worked for URENCO at an enrichment plant for several years. He then used the training he received and the blueprints he stole to spearhead an enrichment program in Pakistan ultimately leading to Pakistan's acquisition of the atomic bomb. Through the black market he provided Iran, Libya and North Korea with various degrees of illicit nuclear assistance, including blueprints for Iran's ongoing enrichment program.[38] While sensitive fuel cycle technology is difficult to acquire through legitimate channels, there are alternatives if a privileged scientist can be persuaded to assist a state illicitly. That states resort to stealing blueprints or attempt to buy them on the black market attests to how difficult it is to develop enrichment or reprocessing facilities without outside assistance.

[35] Iran, of course, benefited immensely from enrichment design information it obtained from Pakistan through the A.Q. Khan network.

[36] The US was willing to provide Canada with a "black box" enrichment plant in which Canada would not have access to the inner workings or design information of the plant.

[37] GNEP was potentially helpful but the Obama administration has ended the program domestically and is likely to considerably recast its international aspects. For a detailed assessment of GNEP see Miles Pomper's forthcoming *Nuclear Energy Futures Paper*, tentatively titled "US International Nuclear Energy Policy: Change and Continuity."

[38] For a more detailed account of Khan's history see Albright and Hinderstein (2005).

Nuclear Device

A peaceful nuclear program does not provide a state with the technology to design and build a nuclear explosive device. In order for a state to do so, it will need to learn, among other things, how to construct explosive lenses (for an implosion type assembly), construct an electrical firing system accurate to a fraction of a microsecond, and build a triggered neutron source to assure a source of neutrons to ignite a chain reaction at the time of firing (Mozley, 1998: 24). Weaponization activities additionally include computer simulations, modeling and calculations, high-energy electrical components and implosion testing, as well as acquiring certain non-nuclear materials such as beryllium, polonium, tritium and gallium.[39] While the designs for these technologies are not readily available in the public domain, they can be acquired by a determined state. For example, Indian and Pakistani scientists were able to learn how to develop neutron initiators in French and Chinese laboratories without attracting suspicion (Perkovich, 2002: 193), though this may not be as easy for a state to do now, given the more robust and encompassing nonproliferation regime.

The shape that fissile material is molded into determines the ease with which it can reach critical mass. Depending on the type of nuclear weapon, a spherical or hemispherical shape is the most common.[40] Fissile material is typically converted into a metal before being used in a nuclear device. The alternative – using oxides without conversion to metal – requires more material and has other disadvantages in bringing the material into an explosive configuration, the end result being a so-called "crude nuclear device" (Mark, [N.D.]). Oxides in the nuclear context refer to the chemical compounds UO_2 and PuO_2 which contain either uranium or plutonium combined with oxygen to make weapons-usable material in a powder and solid form respectively.[41] Casting and machining fissile material into the required shape for a nuclear device is not complicated conceptually, but it is difficult and time consuming to put into practice unless someone with experience is involved (Mark, [N.D.]). Much of this experience is gained through working with fissile material in a peaceful nuclear program, but the machine tools used are highly sophisticated and their export controlled by the NSG (Boyd and Cole, 1994). Even when weapons

[39] Some of these activities are unique to implosion designs. See Carlson et al. (2006).

[40] Gun-type assemblies using enriched uranium involve a hemisphere, while implosion type devices use fissile material in a spherical shape.

[41] For a more detailed analysis of how oxides can be used in a nuclear weapon, see Levi (2007: 67).

usable fissile material has been acquired it is difficult for a state to shape it for a nuclear device. The triggering system of a nuclear device is highly complicated, but not an insurmountable challenge for a determined state. A state's capability to make the leap from power production to assembling a nuclear device is typically considered a matter of time rather than ability. Even assuming the availability of resources, funding, manpower and political support, it often proves to be a lengthy process. It took 13 years for North Korea to detonate its first device after it was caught violating the NPT in 1993. The gap between power production and device assembly is, nonetheless, not marginal and can be prohibitively difficult in some cases, particularly if a state is already under intense international scrutiny and receiving no outside help.

A Uranium versus Plutonium Device

Building a uranium device is considerably easier than its plutonium counterpart. Uranium weapons are typically gun-type assemblies in which a smaller piece of uranium is shot into a larger semi-sphere of uranium in order to reach critical mass and explode.[42] A plutonium device is an implosion device in which explosives are carefully placed around the outside of a sphere of plutonium, causing the plutonium to increase in density upon detonation, thereby creating a critical mass. Plutonium devices require this more complex design because of the spontaneous fission problem relating to certain isotopes of plutonium. Implosion weapons are a significant technical challenge for states without access to nuclear weapon experts, despite explosive lenses and other shaped explosives being more widely used in conventional weapons and commercial applications (NTI, 2009). They are difficult to engineer due to the precision required for detonation.

Some states, notably Pakistan, that have dedicated production reactors to acquire plutonium have failed to build a bomb using it. This may have been the case with North Korea's October 2006 nuclear test, though there is some debate over whether the test was a failed test or a bomb of very low yield.[43] Nonetheless, many states have decided that the relative ease of acquiring plutonium rather than HEU outweigh the difficulties of building a plutonium device. The majority have, as a result, pursued the plutonium path to the bomb.

Assessment

How difficult it is for a state that possesses the necessary material to go on to build either a uranium or plutonium nuclear device is a matter of degree. There are complex steps involved in both that require expertise in areas that are otherwise unrelated to peaceful nuclear energy – not the least of which are the political, organizational and financial factors that have to be conducive to a new military program (Pringle and Spigelman, 1981). The necessary expertise is, however, obtainable for a determined state. Most proliferation experts agree that nearly all states with an industrial infrastructure have the potential to make at least a crude nuclear explosive if they acquire the material.[44] To illustrate this point, two American physicists with no nuclear weapons expertise were able to successfully design a nuclear implosion device using only open source literature in the 1960s as a part of the Pentagon's "Nth Country Project."[45] The non-proliferation regime has therefore determined that its efforts to prevent states from going nuclear should focus on restricting the availability of weapons grade fissile material and not on device design and assembly.

Overview

There is no systematic way to account for all of the connections between a peaceful nuclear program and a nuclear weapons program. Although it is feasible to establish the technical connections between the two in terms of scientific knowledge, there are unquantifiable other benefits a state can derive from a peaceful program related to expertise, personnel, infrastructure and camouflage of a clandestine military program. While these benefits are difficult to measure, they are also the most important to understand.

The scientific knowledge gained from a once-through nuclear program is only the foundation of what is needed to learn to build a nuclear device. It provides a basic foundation in nuclear science and reactor engineering that is essential for a state's scientists to understand, but not nearly sufficient. Additional scientific knowledge

42 The basic principles for a gun-type uranium device are available in the open literature. See NTI (2009).

43 For a more detailed analysis of North Korea's 2006 nuclear test see Reed and Stillman (2009).

44 The Nuclear Threat Initiative reinforces this claim in its technical background of nuclear weapons: NTI, (2009).

45 For a more detailed account of the Nth Country Project see Burkeman (2003).

would need to be obtained about enrichment and/or reprocessing as well as bomb design and construction. The divisions used in this paper – the once-through fuel cycle, sensitive fuel cycle technology and nuclear device design and assembly – represent roughly equal steps, in terms of complexity, towards having the full scientific understanding needed to design and build a nuclear device:

Figure 1: Scientific Knowledge Spectrum

No nuclear capability	Once-through nuclear program	Sensitive fuel cycle technology	Device design and assembly	Full nuclear capability

It is important to note that this scientific knowledge is of secondary importance to the expertise, personnel, infrastructure and camouflage that a peaceful program provides. The possession of the latter enables a state to obtain much of the additional scientific knowledge that is required by using open source literature and, if time is not a pressing issue, by trial and error.[46] Using the same three divisions, the proportions on the broadly defined infrastructure side look much different:

Figure 2: Expertise, Personnel, Infrastructure and Camouflage

No nuclear capability	Once-through nuclear program	Sensitive fuel cycle technology	Device design and assembly	Full nuclear capability

A once-through nuclear program has much more to offer on this side of the equation. Given the robustness of the nuclear export and safeguards regimes now in existence, a state clandestinely seeking nuclear weapons would be all but required to pursue a peaceful energy program first for the purpose of building up the necessary infrastructure. However, safeguards act as a deterrent to diverting a peaceful nuclear energy program to weapons purposes. A state's policy decision to illicitly develop nuclear weapons must inevitably take into consideration that its known peaceful facilities are being closely monitored by the IAEA, and diverting resources would be difficult to conceal.

With a once-through program scientists acquire the basic tools with which to pursue other nuclear-related technologies including enrichment, reprocessing and device design and assembly. It takes time, resources and determination for a state to disregard its international legal obligations and illicitly pursue a technology it has forsworn to pursue. In terms of sheer capability, however, if a state can successfully operate its own reactor fleet it has the potential to pursue nuclear weapons.

Conclusion

Assessing capability is not the same as assessing a state's motivation or the likelihood of new nuclear-armed states emerging. To equate capability with the inevitability of proliferation would be little more than a throwback to long-dismissed theories of technological determinism.[47] Predictions made during the 1960s that dozens of new nuclear-armed states would emerge were incorrect and, barring a drastic change in the global order, predictions that several will emerge in the coming decades are likely as inaccurate.

Every state that does not already have the bomb is legally committed by the NPT to not attempt to acquire one. Reneging on this commitment means noncompliance with international legal obligations and runs risking the backlash of the international community. States like Iran and North Korea that have violated their obligations to various extents have faced what many would view as minor consequences for their noncompliance, so there is a genuine concern that the nonproliferation regime lacks effective enforcement mechanisms. Poor enforcement aside, the vast majority of states do not desire the stigma and repercussions that come with getting caught in pursuit of nuclear weapons. From an international relations perspective, the spread of new peaceful energy programs most likely does not constitute a major proliferation risk, though that is not to say it is entirely risk-free.

There are always exceptions. Iraq, North Korea, Iran, Libya and Syria have all been caught in serious noncompliance with the NPT and it is probable that another state will decide to take its chances at some point. The export control

[46] Contrary to popular belief, detailed weapons designs are not readily available in the open source literature. States have, however, managed to base simpler weapon designs on open source information, such as South Africa's use of American open source information to design its uranium weapon. See Nuclear Threat Initiative (2007). Available at: http://www.nti.org/e_research/profiles/SAfrica/Nuclear/index.html.

[47] Technological determinism stipulated that all states were on a path of technological progress and that their mastery of the atom for a nuclear device was an inevitable part of their development. A belief in technological determinism was common among scientists and politicians in the 1950s and 1960s when fears of nuclear proliferation were arguably at their height.

and safeguards regimes need to be able to detect rare cases of noncompliance as early as possible. The international community has had mixed results historically in dissuading noncompliant states from continuing in their nuclear ambitions. More importantly, however, dozens of states have willingly foregone the nuclear option despite having the capability. Understanding the technical connection between peaceful nuclear energy and nuclear weapons is important, but it is only one consideration. The motivation of states to acquire nuclear weapons, rather than their technical capacity to do so, is the more important concern.

Appendix A: Scientific Disciplines Relevant to Peaceful Programs and Nuclear Weapons

Discipline	Peaceful Uses	Weapons Uses
Nuclear Engineering	Design of nuclear reactors	Dedicated reactors[48]
	Shielding of nuclear reactors and all other types of radiation sources – health physics	Shielding of dedicated reactors and reprocessing plants
	Calculations of radiation doses from radiation facilities during normal operation and under accident conditions	Same
	Calculation of fuel burnup and fissile atom production	Same, particularly plutonium production rate
	Criticality calculations – fuel pools, reprocessing plants, etc.	Same
	Reactor siting and licensing	Developing and running weapon design codes
	Isotope applications	N/A
Chemical Engineering	Design of plants, especially gaseous diffusion, for enriching uranium	Same
	Design of reprocessing plants	Same
	Design of plants for production of heavy water, graphite	Same
	Design of chemical systems required in nuclear power plants	N/A
	Waste disposal systems	N/A
Metallurgical Engineering	Obtaining uranium metal from uranium ore	Same
	Preparation of uranium metal from fron uranium hexafluoride (from enrichment plants)	Same
	Fuel element manufacture	Same
	Materials for reactors: stainless steels, boron carbide, control rod materials, graphite	Same

48 A dedicated reactor refers to a reactor designed specifically to produce plutonium, typically to supply a weapons program.

Discipline	Peaceful Uses	Weapons Uses
		Reduction and purification of plutonium
		Fabrication of plutonium parts of weapons
Mechanical Engineering	Design of reactor structures	Same, dedicated reactors
	Heat transfer calculations for reactors	Same, dedicated reactors
	Design of steam generators, pressurizers, pumps, heaters, condenser, piping	Design of structural components of weapons
	Centrifuges for isotope separation	Same
	Mechanical design of fuel handling equipment, fuel casks, etc.	Same
	Heating ventilating, air conditioning	N/A
Electrical Engineering	Reactor instrumentation and control systems	Same, dedicated reactors
	Electric generation and distribution systems for nuclear power plants	Ignition systems for weapons
	Instrumentation and control of reprocessing plants, isotope enrichment plants	Same
Physics	Measurement of fundamental nuclear data for reactor design	Fundamental design calculations of weapons-the amount and distribution of uranium or plutonium, the explosive configuration, the location of the igniters, the weapon yield, and effects of weapon detonation
	Fundamentals of isotope separation, lasers, centrifuges, etc.	Same
Mathematics and Computer Science	Codes for reactor design and operation	Assist in calculations used in weapons design-developing the necessary codes
	Shielding design, radiation dose code	N/A
	Statistical analysis of reactor components, accident probabilities	N/A
Chemistry	Design, operation of chemical systems in nuclear power plants	Same, dedicated reactors
	Provide fundamental chemical data for design of reprocessing plant	Same

Source: Comptroller General of the United States, 1979.

Appendix B – Items Considered Dual-use by the Nuclear Suppliers Group (INFCIRC/254/Rev.9/Part.1)

For further explanation of the items listed below see the source document cited on page 16.

1. *Nuclear reactors and especially designed or prepared equipment and components therefor*
   - Complete nuclear reactors
   - Nuclear reactor vessels
   - Nuclear reactor fuel charging and discharging machines
   - Nuclear reactor control rods and equipment
   - Nuclear reactor pressure tubes
   - Zirconium tubes
   - Primary coolant pumps
   - Nuclear reactor internals
   - Heat exchangers
   - Neutron detection and measuring instruments

2. *Non-nuclear materials for reactors*
   - Deuterium and heavy water
   - Nuclear grade graphite

3. *Plants for the reprocessing of irradiated fuel elements, and equipment especially designed or prepared therefor*
   - Irradiated fuel element chopping machines
   - Dissolvers
   - Solvent extractors and solvent extraction equipment
   - Chemical holding or storage vessels

4. *Plants for the fabrication of nuclear reactor fuel elements, and equipment especially designed or prepared therefor*

5.1 *Plants for the separation of isotopes of natural uranium, depleted uranium or special fissionable material and equipment, other than analytical instruments, especially designed or prepared therefor*
- Gas centrifuges and assemblies and components especially designed or prepared for use in gas centrifuges
- Rotating components
- Static components

5.2 *Especially designed or prepared auxiliary systems, equipment and components for gas centrifuge enrichment plants*
- Feed systems/product and tails withdrawal systems
- Machine header piping systems
- Special shut-off and control valves
- UF6 mass spectrometers/ion sources
- Frequency changers

5.3 *Especially designed or prepared assemblies and components for use in gaseous diffusion enrichment*
- Gaseous diffusion barriers
- Diffuser housings
- Compressors and gas blowers
- Rotary shaft seals
- Heat exchangers for cooling UF6

5.4 *Especially designed or prepared auxiliary systems, equipment and components for use in gaseous diffusion enrichment*
- Feed systems/product and tails withdrawal systems
- Header piping systems

- Vacuum systems
- Special shut-off and control valves
- UF6 mass spectrometers/ion sources

5.5 *Especially designed or prepared systems, equipment and components for use in aerodynamic enrichment plants*
- Separation nozzles
- Vortex tubes
- Compressors and gas blowers
- Rotary shaft seals
- Heat exchangers for gas cooling
- Separation element housings
- Feed systems/product and tails withdrawal systems
- Header piping systems
- Vacuum systems and pumps
- Special shut-off and control valves
- UF6 mass spectrometers/Ion sources
- UF6/carrier gas separation systems

5.6 *Especially designed or prepared systems, equipment and components for use in chemical exchange or ion exchange enrichment plants*
- Liquid-liquid exchange columns (Chemical exchange)
- Liquid-liquid centrifugal contactors (Chemical exchange)
- Uranium reduction systems and equipment (Chemical exchange)
- Feed preparation systems (Chemical exchange)
- Uranium oxidation systems (Chemical exchange)
- Fast-reacting ion exchange resins/adsorbents (Ion exchange)
- Ion exchange columns (Ion exchange)
- Ion exchange reflux systems (Ion exchange)

5.7 *Especially designed or prepared systems, equipment and components for use in laser-based enrichment plants*
- Uranium vaporization systems (AVLIS)
- Liquid uranium metal handling systems (AVLIS)
- Uranium metal “product” and “tails” collector assemblies (AVLIS)
- Separator module housings (AVLIS)
- Supersonic expansion nozzles (MLIS)
- Uranium pentaflouride product collectors (MLIS)
- UF6/carrier gas compressors (MLIS)
- Rotary shaft seals (MLIS)
- Fluorination systems (MLIS)
- UF6 mass spectrometers/ion sources (MLIS)
- Feed systems/product and tails withdrawal systems (MLIS)
- UF6/carrier gas separation systems (MLIS)
- Laser systems (AVLIS, MLIS and CRISLA)

5.8 *Especially designed or prepared systems, equipment and components for use in plasma separation enrichment plants*
- Microwave power sources and antennae
- Ion excitation coils
- Uranium plasma generation systems
- Liquid uranium metal handling systems
- Uranium metal “product” and “tails” collector assemblies
- Separator module housings

5.9 *Especially designed or prepared systems, equipment and components for use in electromagnetic enrichment plants*
- Electromagnetic isotope separators
- High voltage power supplies
- Magnet power supplies

6. *Plants for the production or concentration of heavy water, deuterium and deuterium compounds and equipment especially designed or prepared therefor*
- Water-hydrogen sulphide exchange towers
- Blowers and compressors
- Ammonia-hydrogen exchange towers
- Tower internals and stage pumps
- Ammonia crackers
- Infrared absorption analyzers
- Catalytic burners
- Complete heavy water upgrade systems or columns therefor

7.1 *Plants for the conversion of uranium and plutonium for use in the fabrication of fuel elements and the separation of uranium isotopes as defined in sections 4 and 5 respectively, and equipment especially designed or prepared therefor*
- Plants for the conversion of uranium and equipment especially designed or prepared therefore
- Especially designed or prepared systems for the conversion of uranium ore concentrates to UO3
- Especially designed or prepared systems for the conversion of UO3 to UF6
- Especially designed or prepared systems for the conversion of UO3 to UO2
- Especially designed or prepared systems for the conversion of UO2 to UF4
- Especially designed or prepared systems for the conversion of UF4 to UF6
- Especially designed or prepared systems for the conversion of UF4 to U metal
- Especially designed or prepared systems for the conversion of UF6 to UO2
- Especially designed or prepared systems for the conversion of UF6 to UF4
- Especially designed or prepared systems for the conversion of UO2 to UCl4

7.2 *Plants for the conversion of plutonium and equipment especially designed or prepared therefor*
- Especially designed or prepared systems for the conversion of plutonium nitrate to oxide
- Especially designed or prepared systems for plutonium metal production

Source: IAEA (2007).“Communication Received from the Permanent Mission of Brazil regarding Certain Member States’ Guidelines for the Export of Nuclear Material, Equipment and Technology,” INFCIRC/245/Rev.9/Part.1. November 7. Available at: http://www.iaea.org/Publications/Documents/Infcircs/2007/infcirc254r9p1.pdf.

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