Science and Global Security, 13:183–207, 2005

ISSN: 0892-9882 print
DOI: 10.1080/08929880500357708

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Nuclear Proliferation with Particle Accelerators

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The use of accelerators to produce ^{239}Pu or ^{233}U is compared to the production of these materials in a small nuclear reactor. The comparison is given in terms relevant to an entry-level proliferator. Production rates, technological complexity, methods of acquisition, costs, and detection methods are compared.

INTRODUCTION

It is generally recognized that the acquisition of fissile material is the largest obstacle to making nuclear weapons. Traditionally, this involves either enrichment technologies, used to extract fissile ^{235}U from natural uranium; or nuclear reactors, used to produce man-made fissile materials, namely ^{239}Pu or ^{233}U. Both routes have long been the focus of nonproliferation controls. Particle accelerators, by contrast, have not been accounted for by nonproliferation controls, but can also produce weapon-usable fissile material.

Historically, accelerator-based methods were grossly uneconomic, if not infeasible, routes for proliferators. However, the general spread of technological know-how, specific advances in simple accelerator designs, and an increase in the legitimate uses for accelerators are changing this calculation. Though the acquisition of fissile material via particle accelerators continues to be technically challenging, to do so is substantially easier today than it was several decades ago.

There are no inspection requirements for accelerator facilities under existing International Atomic Energy Agency (IAEA) safeguards, and no restrictions specifically barring the international transfer of the relevant accelerator technologies under any multilateral export-control framework.[1] These

Received 10 November 2004; accepted 5 January 2005.
This research was made possible by the generous support of the J. William Fulbright Program and the Program on Science and Global Security at Princeton University.
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two factors—the wide availability of accelerator technology and lack of institutionalized monitoring—are primary incentives for producing fissile material with particle accelerators. Export controls would go far in removing these incentives by controlling key technologies needed by unsophisticated proliferators and improving intelligence about a proliferator's objectives.

CONSIDERATIONS FOR PROLIFERATION TECHNOLOGIES

On his route to producing fissile material, the technologically-unsophisticated proliferator[2] is faced with a number of considerations, such as bomb design, production rates, technical complexity, affordability, resource availability, and political issues. A cursory review of his options are given here to set the parameter space in which the following analyses take place.

A proliferator needs only one or two bombs to be considered a de facto nuclear weapon state. As such, the proliferator may choose from technologies that do not scale well, or those that are considered too inefficient for large-scale production. This article takes as a reference case the production of one bomb's worth of fissile material in a period of two years, with the specific amount of material adjusted according to the bomb design.

Given a decision to acquire fissile material, a proliferator must decide between types of fissile material and, further, the means of acquiring it. There are three relevant fissile materials and two basic methods of acquisition. ^{235}U is a fissile material obtained by isotopic enrichment of natural uranium. ^{239}Pu and ^{233}U are man-made fissile materials produced when an atom of fertile material absorbs a neutron. These neutrons may come from a nuclear reactor or particle accelerator.

This article aims to evaluate the risks associated with particle accelerators in comparison to a nuclear reactor. The scope is limited to "indigenous technologies" (i.e., made domestically from entirely native or open-market resources) and "dedicated programs" (i.e., not used for other than weapon purposes).

Weapon-usable plutonium, consisting primarily of ^{239}Pu, is produced from fertile ^{238}U. It is desirable to minimize spontaneous neutron emission by minimizing the isotopic contaminant ^{240}Pu. Plutonium with less than seven percent ^{240}Pu content is frequently called "weapon-grade," and can be readily produced in a nuclear reactor operated at low fractional burn-up, or with a particle accelerator.[3] Even weapon-grade plutonium has a relatively high rate of spontaneous neutron emission, and thus can be used only in an "implosion-type" weapon. Implosion minimizes the risk of predetonation, a phenomenon in which the weapon's yield is only a fraction of its potential. A fractional yield is not necessarily an impediment, as it would be sufficiently destructive for many purposes.

Implosion weapons are also more difficult to build. Full confidence that a new implosion design will function comes only from nuclear testing. However,

testing reveals ownership of a nuclear weapon and can place the proliferator into a politically-undesirable situation.[4]

^{233}U is made from fertile ^{232}Th. It has a much lower spontaneous neutron background and will not suffer from predetonation like plutonium. It can be used in a simple gun-type assembly; a weapon design that does not require testing. However, a gun-type weapon typically requires more than double the amount of fissile material than does an implosion-type weapon. This article assumes 20 kg of ^{233}U is needed for a gun-type weapon.

As with plutonium, the production of ^{233}U results in an undesirable isotopic contaminant. The contaminant ^{232}U has a decay chain that produces penetrating gamma radiation.[5] These gamma rays increase in intensity for about a decade after the uranium is synthesized, and at sufficient levels become hazardous to workers. ^{233}U with ^{232}U concentrations low enough to permit many months of exposure[6] can be produced in several ways. One method accessible to the entry-level proliferator involves placing thorium targets in a natural-uranium-fueled graphite or heavy-water reactor. However, only just over seven percent of the reactor's loading can be thorium before the reactor becomes subcritical.[7] As the preponderance of neutrons will be captured by ^{238}U present in the natural-uranium fuel, a reactor of about 13 times the size is required for ^{233}U production compared to that used for plutonium production.[8] Such sizeable reactors are likely to be outside the capability of an entry-level proliferator and almost certainly prone to early detection.[9]

A SMALL PLUTONIUM PRODUCTION REACTOR: A BASELINE FOR COMPARISON

A 1977 report of the United States Congress, Office of Technical Assessment (OTA) considered small nuclear reactors an easy route to fissile material for an entry-level proliferator.[10] It gives as an example a 25-MWt nuclear reactor that might produce about 7 kg of weapon-grade plutonium per year,[11] just short of the 8 kg needed for one first-generation (Nagasaki-type) implosion bomb.[12] The reactor construction requirements are summarized here and used as a baseline to which particle accelerators are compared.

Only reactors known to function with unenriched uranium are considered (if a proliferator could enrich uranium, he could simply produce a ^{235}U weapon directly). Only graphite and heavy-water moderated reactors are known to function with natural-uranium fuel. As a nonproliferation control, both reactor-grade graphite and heavy water are export-controlled materials.

Despite export controls, reactor-grade graphite (having less than 5 ppm boron) may be produced indigenously. The manufacturing process is essentially the same as for electrode-grade graphite.[13] Petroleum coke is treated in an oxygen-free oven until impurities sublime or evaporate away. The extra

boron contaminants are removed by raising the temperature of the oxygen-free ovens.[14]

The Brookhaven Graphite Research Reactor (BGRR), built in 1948 and now shut down, serves as a good example of what an entry-level graphite reactor might look like today.[15] It is constructed from a 25-foot cube of graphite penetrated by a square matrix of air channels, 37 per side. Finned fuel elements were placed in the center of the channels and air passed between them and the graphite as a coolant. A simplified proliferator version would require about 75 metric tonnes of natural uranium fuel, and 415 metric tonnes of graphite.[16] The OTA estimated the construction of this simplified version would require 1 civil-structural engineer, 1 electrical engineer, 2 mechanical engineers, 3 nuclear engineers, and 1 metallurgist; two to four years of work; and $13.3 million in capital costs.[17]

PARTICLE ACCELERATORS

The ability of particle accelerators to produce manmade fissile materials has long been known (see box: History of Electronuclear Breeding). Although established nuclear states have favored reactors for reasons of cost and reliability, these case examples cannot inform questions about entry-level proliferation. Established nuclear powers and technologically-sophisticated states need not contend with export controls, limited material resources or technical expertise, and clandestine objectives; the entry-level proliferator must. Some characteristics of particle accelerators are favorable under these particular constraints. Indeed, particle accelerators are useful simply because they are not nuclear reactors; their otherness currently places their technologies safely outside the nonproliferation community's watchful eye. Today, a proliferator may be able to construct a particle accelerator at leisure, even solicit foreign assistance, and yet raise no suspicions as to his objectives. Nuclear reactors are less likely to offer such invisibility. This shortcoming of nonproliferation controls may encourage a proliferator to choose particle accelerators, even if they are not competitive in terms of yield, cost, or technical ease.

That accelerators have not yet been exploited by proliferators may be due to the method's obscurity or to a difficulty in acquiring appropriate accelerator technology. These factors are changing. Over the last decade, several research groups have proposed using accelerators to dispose of high-level actinide waste. These efforts have generated a substantial body of literature that serves to remove the obscurity of accelerator-based transmutation and inform any proliferator seeking guidance on the method.[18] Moreover, the last decade has also seen many advances in the commercial availability of accelerators and the development of inexpensive high-current accelerators for cancer therapy.

HISTORY OF ELECTRONUCLEAR BREEDING

Particle accelerators were used to transmute isotopes as early as 1930, and in 1941 Glenn Seaborg and his team produced the first microgram quantities of ^{239}Pu by bombarding ^{238}U with 6-MeV deuterons. However, none of these early methods produced more than one neutron per accelerated particle and, without modern high-current accelerator designs, all were inefficient for transmutation.

In 1947, while studying cosmic rays with boron-trifluoride counters, Vanna Coconi realized that high-energy particles moving through matter were the sources of many neutrons. A year later, R. H. Goeckerman and I. Perlman observed that a 190-MeV deuteron-bismuth reaction yielded 12 neutrons per deuteron. This phenomenon, now called spallation, made possible the large-scale conversion of isotopes with accelerators. The ability to exploit spallation for nonpeaceful purposes was immediately recognized and within two years of its discovery the Materials Testing Accelerator (MTA) program was founded.

The 1950 MTA program was sited on an abandoned U.S. Army installation in Livermore, California. Its purpose was to produce weapon plutonium from surplus depleted uranium left over from U.S. enrichment activities. At the time, the United States was dependent on South Africa for its uranium, a byproduct of gold mining. A plutonium-production program was planned to free the United States from dependency on foreign states for fissile material. The United States launched the MTA program in direct competition to the plutonium-production reactor at Hanford. The MTA also competed with the Savannah River facility for the production of tritium, used to boost the yield of nuclear explosives. By 1952, the MTA project had a 500-mA, 350-MeV linear deuteron accelerator called A-12, which produced transmuting neutrons with a beryllium spallation target.

Two years and several accelerators later the program was terminated. Rich uranium deposits had been discovered in the United States and the Department of Energy concluded that it could not successfully complete the device. E.O. Lawrence, who ran the MTA program, eventually received a patent for his invention, and although the project never took wing, it gave birth to the Lawrence Livermore National Laboratory, now one of the United States' leading nuclear-weapon-science centers.

Accelerator-based plutonium production has since been reconsidered numerous times. Canada had initial plans for an "electronuclear breeder" as early as 1951 and continued to entertain the concept through at least 1981; Russia explored systems in the 1960s and 1970s; and several U.S. national laboratories made proposals throughout the 1970s, including a multilab program called FERFICON that ran from 1975 to 1988. Most recently the United States and France independently considered producing tritium with particle accelerators.

References:

General: P. Grand, "The Use of High Energy Accelerators in the Nuclear Fuel Cycle," *Nature* 178: 19 April 1979; Richard Wilson, "Accelerator Driven Subcritical Assemblies," a report to the Energy, Environment and Economy Committee, U.S. Global Strategy Council, Harvard June 20, 1998; MTA reports UCRL-79151 (LLNL), 1977; UCRL-52144 (LLNL) 1976; BNL-50592, 1976; J. Magill and P. Peerani, "(Non-) Proliferation Aspects of Accelerator Driven Systems," *Journal de Physique IV*, France 9 (1999). *Canadian Projects:* W.B. Lewis, "The Significance of the Yield of Neutrons from Heavy Nuclei Excited to High Energies," Atomic Energy of Canada Limited (AECL) Research and Development Report, August 25, 1952 AECL-DR-24; Other AECL reports AECL-969, 1953; AECL-3190, 1968. *Tritium Projects:* J. F. Tooker, R. Bourque, D. Christiansen, J. Kamperschroer, G. Laughon, M. McCarthy, M. Schulze, *Overview of the APT Accelerator Design*, General Atomics (San Diego, CA), TUD06.

TECHNICAL CONSIDERATIONS FOR PARTICLE ACCELERATORS

Particle accelerators have the potential for finer control over the transmuting environment than do nuclear reactors. By finely tuning neutron energies and moderating characteristics, one can preferentially select for the desired neutron-capture reactions while minimizing the undesired reactions that lead to isotopic contamination, such as (n,2n) and fissions.

In the production of fissile material, there are several ways to exploit this flexibility inherent to particle accelerators. For plutonium production, the production rate can be maximized while maintaining acceptable levels of isotopic contamination. Alternatively, fissions—which are responsible for most of the radioactivity and detectable effluents present in spent reactor fuel—can be minimized, thereby enhancing safety, simplifying reprocessing operations, and theoretically reducing the probability of detection. These effects are controlled by the design of the transmuter.

The level of isotopic contamination depends principally on the neutron flux experienced by the fertile material multiplied by the amount of time it is exposed, also called the "burn-up". In heavy-water and graphite-moderated reactors, frequent replacement of fuel elements is possible allowing isotopic contamination to be kept low. Accelerators thus provide no significant advantage over reactors in this regard. However, there is no way to minimize radioactivity and detectable effluents in a nuclear reactor. These arise from fissions, the fundamental action of reactors, which also produce the needed neutrons. Accelerators produce neutrons differently, so they can minimize radioactivity and effluents.

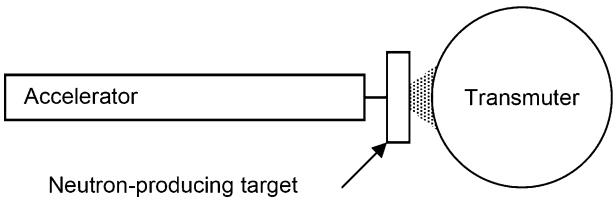

Figure 1: Schematic diagram of an accelerator-driven fissile-material production system.

All the above considerations also apply to ^{233}U production. Accelerators may also offer an additional benefit when producing ^{233}U. Fairly large nuclear reactors are required to produce enough ^{233}U for a bomb in a reasonable amount of time. As such, accelerators may offer a smaller-scale approach, more in keeping with the abilities of an entry-level proliferator.[19]

ACCELERATOR-BASED SYSTEM CONFIGURATIONS

Three types of hardware comprise the accelerator-based system, as shown in Figure 1. To the right of the diagram is the transmuter. It contains the fertile material and provides the desired neutronic conditions for transmutation. Two types are considered here: multiplying and nonmultiplying. In the center is the neutron-producing target that converts ions of a specific species and energy to neutrons via one or more nuclear reactions. Three types are considered: spallation, photonuclear reactions, and (p,n) and (d,n) reactions. Finally, the accelerator, on the left of the diagram, provides ions to feed the neutron-producing target. Six types are considered: conventional cyclotrons, isochronous cyclotrons, synchrocyclotrons, linear proton accelerators, linear electron accelerators, and electrostatic quadrupole accelerators. These 11 items can be assembled in various configurations[20] to achieve different objectives and in accordance to the proliferator's particular restrictions and resources.

The Transmuter

This component determines the transmutation environment by its geometry and the materials of its construction. The two transmuters presented here represent practical endpoints to a spectrum of options. In one, a nonmultiplying transmuter is designed to restrict neutrons to those energies that favor desired nuclear reactions and, in doing so, minimizes undesired reactions, like fissions. This helps to reduce the production of isotopic contaminants and lessen the radioactivity of the unreprocessed product. The other transmuter, a multiplying design, trade fine-tuned reactions for higher production rates. It emphasizes fissions in order to multiply source neutrons.

A **nonmultiplying transmuter** might take a form similar to that proposed by CERN's Accelerator Transmutation of Waste Program: a large cube of

lead,[21] five meters per side, with the neutron source at the center. A matrix of channels could be drilled into the volume at an appropriate distance from the neutron source and filled with fertile material.[22] Experimental results show that a solid lead cube of this size could successfully contain 96 percent of high-energy neutrons.[23] Lead acts as a scattering material that slows neutrons by elastic collisions. The energy of a scattered neutron in the laboratory-reference frame is given by the equation:

$$E_n' = E_n \cdot (A^2 + 2 \cdot A \cdot \cos\theta + 1)/(A+1)^2, \tag{1}$$

where E_n and E_n' are the energies of the incident and scattered neutron, respectively; A is the atomic mass of the scattering nucleus (208 in the case of lead); and θ is the scattering angle.[24] Owing to lead's heavy atomic mass, the change in the neutron's energy is very small compared to the width of the resonance-capture region in the fertile material (typically extending over some 3 keV, with individual resonances having about 1 eV full width at half maximum). Indeed, the energy change is often so small as to be smaller than the distance between two adjacent capture resonances. This allows neutrons to moderate slowly through the resonance region, thus maximizing the probability of capture before reaching regions where fission and other reactions might dominate.[25] To illustrate this effect, Figure 2 shows on linear axes a small subsection (17%) of the neutron-capture resonance-region for ^{232}Th. Twenty-two

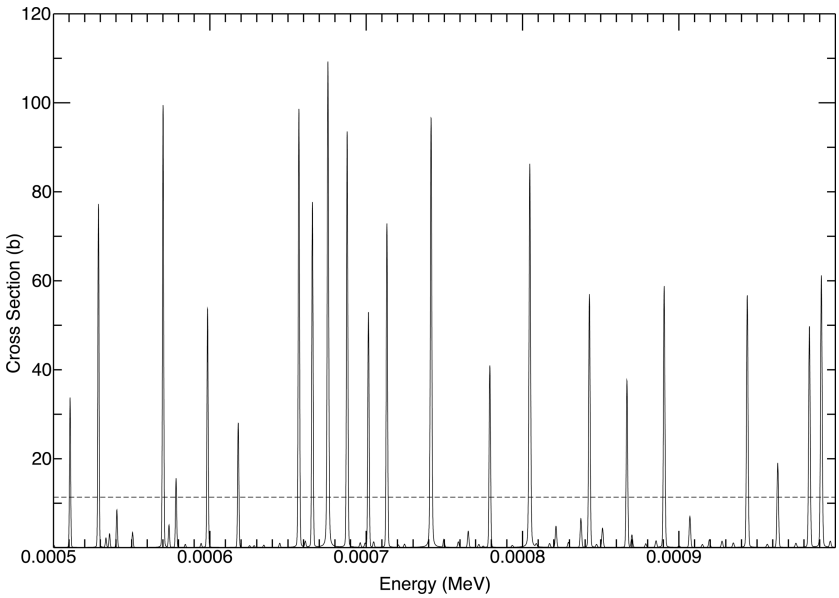

Figure 2: Cross-section plot for ^{232}Th(n, y) (solid) and ^{208}Pb(n,n) (dashed) showing 22 ~1 eV wide capture resonances with cross-sections above the scattering cross-section for lead. About seventy-three 90° scatters would be needed for a neutron to traverse the same region.

resonance lines (with cross-sections larger than the scattering cross-section for ^{208}Pb) appear in this region. A neutron would need to scatter at 90° some 73 times in order to traverse the region occupied by the 22 resonance lines. Over the entire resonance region, the high number of scatters gives a high probability that the neutron is captured by a resonance in the fertile material before reaching thermal energies where fissions of fertile material become the dominant reaction.

The fissile material production rate is increased markedly by using a **neutron-multiplying transmuter**. The classical nuclear-reactor core, made subcritical by the use of a non-reactor-grade moderator or unenriched fuel, can function as a neutron-multiplying transmuter when attached to a particle accelerator. Such subcritical reactors are more forgiving both in design and operation than normal nuclear reactors. They do not require control mechanisms by virtue of their subcriticality, and wider fluctuations in the reactivity are tolerated. A study of such transmuters found that fissile-material production could be practically increased by a factor of more than 10 over that of the nonmultiplying transmuter.[26] The control of isotopic composition cannot be done by controlling the neutron energies, as with the lead-block moderator. Instead, the ingrowth of undesirable isotopes is reduced by limiting the fractional burn-up of the fuel. Since the core relies on the fission of fissile nuclei, it must be loaded with a mix of fertile and fissile materials, such as natural uranium. The core is thus limited in its ability to produce ^{233}U in the same way that nuclear reactors are. Special hybrid systems, having both a neutron multiplying region fueled with natural uranium and a nonmultiplying region filled with thorium fertile material, can enhance the production rate of ^{233}U compared to the lead-block transmuter, though not to the same extent as the subcritical-reactor transmuter.[27]

The Neutron-Producing Target

Accelerators can produce neutrons via spallation, photonuclear reactions, and those reactions known as (p,n) and (d,n). Each mechanism works best in a particular energy region. This limits the accelerators that can be practically used for any given mechanism. If a proliferator is able to acquire an accelerator only of a specific type, he may be forced to choose a neutron-production reaction of lower efficiency. The compatibility of accelerators and reactions is shown in Figure 5.

In **Spallation** neutron sources, a high-energy proton[28] impinges on a heavy nucleus (an atom in the target) and causes the release of many neutrons. It is the most energy-efficient method of producing neutrons with particle accelerators considered here. Detailed studies of spallation and the associated engineering challenges are widely available in the open literature. The challenge for spallation is that it requires a high-energy, high-current proton beam, which is not available from simple accelerator designs.

The spallation neutron yield depends strongly on the target composition and geometry, and on the energy of the impinging proton. For a cylindrical depleted-uranium[29] target, 10 cm in diameter and 60 cm in length, the macroscopic neutron yield per source proton can be approximated by the empirical formula:

$$Y_{n/p} = 0.0367 \cdot (E_p - 120) \quad \text{for} \quad E_p > 120 \text{ MeV} \tag{2}$$

where E_p is the energy of the impinging proton.[30] Note that the yield is approximately one-to-one at 150 MeV. Below energies of around 100 MeV, the neutron yield drops quickly. Beam currents need to be in the tens or hundreds of milliamp range for reasonable production rates.[31] These energies and currents are generally unattained in common accelerators.

In **Photonuclear** neutron sources, high-energy electrons are ejected into a target where their energy is largely converted into photon energy through Bremstrahlung radiation. These photons interact with nuclei to produce neutrons. It is found experimentally that neutron production is most efficient when the energy of the electron beam is between 100 and 200 MeV, and energies in this range are used in laboratory electron accelerators used for neutron production. However, the production rate is still fairly linear to about 1 GeV.[32] A thick, high-density natural-uranium target gives[33]:

$$Y_{n/e} = 6.3 \times 10^{-4} \cdot E_e - 7.5 \times 10^{-3} \quad \text{for} \quad 16 < E_e < 200 \text{ MeV} \tag{3}$$

Photonuclear neutron production is less energy-efficient than spallation. For a technology that is already energy-intensive, it would seem a limiting factor. However, one study found that the lower cost of electron accelerators (as compared to proton accelerators) could offset the increase in energy costs provided neutron requirements were below 10^{17} neutrons per second—which is approximately half of what is required to produce 8 kg of plutonium in two years with a neutron-multiplying transmuter.[34]

(p,n) and (d,n) neutron sources produce neutrons from light elements with protons or deuteron of just a few MeV. The lower energy requirement greatly simplifies the accelerator technology required, making these reactions particularly accessible to the entry-level proliferator. Such reactions include ^{7}Li(p,n), ^{9}Be(p,n), and ^{9}Be(d,n). Of these, ^{7}Li(p,n) is the most efficient,[35] with a yield given by the equation:[36]

$$Y_{n/p} = 2.0 \times 10^{-5} \cdot E_p^{2.5} \quad \text{for} \quad 2.0 < E_p < 7.0 \text{ MeV} \tag{4}$$

Figure 3 shows the yield in neutrons per ion (i.e., per proton or electron, as appropriate) for each of the reactions considered above. Spallation gives the best yield, but requires high energy protons. Photonuclear reactions (with electron accelerators) can give similar neutron yields as (p,n) reactions, but require more energy per ion. Photonuclear reactions are thus favorable only

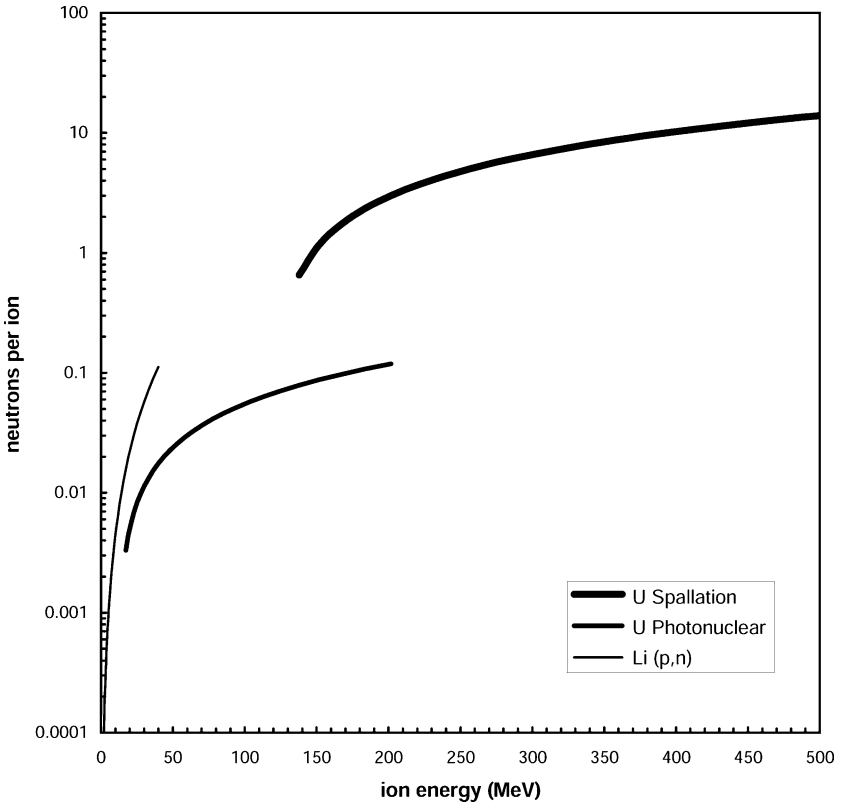

Figure 3: Relatively yields of neutron production reactions.

when electron accelerators are more readily acquired than proton accelerators. The Li(p,n) reaction shows poor performance compared to spallation, but enable the proliferator to exploit low-energy accelerators.

The Particle Accelerator

Particle accelerators are the most technologically-complex component in an accelerator-driven system. Only machines that can accelerate protons to energies greater than 2 MeV, or electrons to energies above 16 MeV, are compatible with one or more of the neutron reactions detailed previously. High-current beams are required to produce material at a reasonable rate. In cases where a particular accelerator cannot provide enough current to meet production demands, multiple machines can be used in parallel. Machines with both appropriate energies and sufficient beam current are uncommon and their acquisition may pose a challenge. Possible sources include commercial turnkey systems, and domestically-constructed accelerators made with or without foreign assistance. Older and simpler technologies are more accessible candidates

for indigenous manufacture than are the advanced designs of the last several decades.

For a given neutron-production reaction and accelerator beam energy, the electricity consumed is in direct proportion to the number of neutrons produced. The specific power requirements depend on the neutron-production mechanism used (e.g., spallation, photonuclear, etc.), the transmuter design selected (neutron multiplying or non-neutron-multiplying), and other aspects that affect the overall performance of the system (neutron economy, reprocessing losses, efficiency, etc.). For weapons production, this electricity is a substantial cost and may diminish the attractiveness of accelerators. In some cases, a proliferator may have to build a dedicated power-generation facility. Although electricity will be a major component of expenditure, the annual cost of several accelerator-based systems are within the estimated construction cost of a BGRR-like nuclear reactor.

The following parameters are used in subsequent calculations of electricity use and cost. Accelerators are assumed to operate at 50% electrical efficiency. This is typical of commercially-available accelerators. Crudely-built accelerators, especially those operating with a poor vacuum in the beam cavity, may operate at lower efficiencies. The facility is assumed to operate at full power for 80% of the time. Reprocessing losses are estimated at 2%. Electricity is assumed to cost \$0.06/kWh.[37]

For comparison purposes, an industrial facility might consume 10–50 MW of electricity. Were new electricity resources required, the proliferator could purchase preengineered gas-turbine generators for about \$400,000 capital cost per megawatt of capacity, with a operating cost of about \$0.04/kWh.[38]

Conventional cyclotron technology dates back to 1931. Conventional cyclotrons are limited by relativistic effects to energies below approximately 25 MeV. This is hardly enough energy to penetrate the uranium nuclei's coulomb barrier and thus not even capable of low-yield spallation. Such reactors can be used with (p,n) reactions, though high beam currents are required. Without focusing mechanisms, space-charge effects limit beam currents to tens or hundreds of microamps.[39] Even at 500 μA and 25 MeV, some 250 cyclotrons would be needed when coupled with the neutron-multiplying transmuter. This configuration would use about 6.2 MW of electricity, costing some \$5.2 M per implosion bomb.

Isochronous cyclotrons have radially-varying magnetic fields that compensate for relativistic effects, permitting the high energies necessary for spallation. Often isochronous cyclotrons also employ azimuthally-varying magnetic fields or sector focusing,[40] a method of overcoming space-charge effects to achieve higher beam currents. However, these cyclotron enhancements may prove a significant engineering challenge for a technologically-unsophisticated proliferator. Their implementation is arguably more complex than building a small plutonium production reactor. For example, the 88-inch cyclotron built in

1958 at Lawrence Berkeley Laboratory was an early isochronous cyclotron. It took more than a score of the then best accelerator scientists about four years to move from first design to the first successful operation.[41] By comparison, a small plutonium-production reactor is estimated to take eight scientists about two to four years to complete.[42]

Isochronous, sector-focused cyclotrons are available commercially. The private firm, Ion Beam Applications (IBA) in Belgium, advertises a 150 MeV, 2 mA cyclotron that could produce 960 g of plutonium per year with a neutron multiplying transmuter, or 68 g of fissile material with the lead-block transmuter. This cyclotron is reportedly priced around $40 M. About four of these cyclotrons would be needed to produce one bomb in two years with the subcritical reactor. The accelerators would consume 18 MW of electrical power per implosion bomb, costing some $15 M.

Another IBA cyclotron has a stated beam energy of 18 MeV and 2 mA, though its beam current could be improved by upgrading the ion source. The cyclotron's space-charge limit is between 5 and 10 mA.[43] At an output of 10 mA, it could produce 147 g of plutonium per year with the multiplying transmuter. Twenty-seven cyclotrons would be needed to make 4 kg of plutonium per year, with power requirements at 9.8 MW, costing $10 M per implosion bomb.

Synchrocyclotrons compensate for relativistic lag by varying their magnetic-field oscillation frequency in time. As a consequence, the machine is inherently pulsed because only one bunch of particles can be accelerated at a time. Although the particles can reach substantial energies (700 MeV or more), the pulsed quality typically limits the average current to a few microamperes, and thus synchrocyclotrons are not practical for weapons production.[44]

Linear proton accelerators are capable of producing both the high currents and high energies needed for spallation. The accelerators built in 1950 for the MTA fissile-material-production program[45] were of this design. In theory, a linear accelerator capable of many bombs per year could be built. However, in most applications, cyclotrons are preferred over linear accelerators, and commercially made versions are not available. This suggests that linear proton accelerators are at least as difficult to construct as isochronous cyclotrons. By extension, if we should consider isochronous cyclotrons more difficult to construct than small nuclear reactors, then we should regard linear proton accelerators as more difficult still. Foreign assistance, however, could negate this argument, and such assistance could presently go unnoticed.

Linear electron accelerators are easier to construct than their proton counterparts. Electrons reach relativistic speeds at lower energies than protons, owing to their small rest-mass, and thus the accelerator's drift-tubes can be made all the same length. Though these accelerators might prove more practical

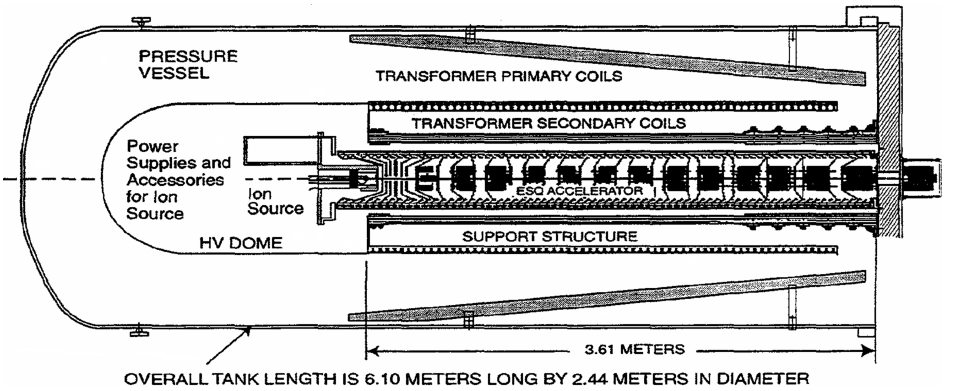

Figure 4: Cut-away view of a 2.5 MeV 125 mA electrostatic quadrupole accelerator showing ion source, pressure vessels, and inductively-coupled high-current power supply. From B.A. Ludewigt et al., *An Epithermal Neutron Source for BNCT based on an ESQ-Accelerator,* Ernest Orlando Lawrence Berkeley National Laboratory, July 1997.LBNL-40642.

than most proton accelerators for indigenous production, they still require a technical sophistication beyond that of the simple cyclotron.

Electrostatic quadrupole accelerators (ESQs) are the most simple accelerator considered here (see Figure 4.) They are capable of accelerating protons to 2.5 MeV in a "single," and 5 MeV in a "tandem." Quadrupole focusing allows for particularly high beam currents, enabling the successful exploitation of the (p,n) reaction. The limiting factor for ESQs is the current achievable in the power supply. Designs of over 100 mA have been demonstrated, and of 1000 mA have been proposed. Assuming a tandem-accelerator's 5 MeV beam energy, and 100 mA current, some 50 accelerators would be required to produce one implosion bomb in two years when coupled with a subcritical-reactor transmuter.[46]

Figure 5 shows the compatibility of various accelerators with the three neutron production reactions discussed above. The ordinate axis gives the total power required to obtain enough fissile material for an implosion-type bomb (8 kg) over a two-year period. These values are given for the nonmultiplying transmuter on the left of the chart, and for a multiplying transmuter on the right of the chart.[47] Characteristic beam energies for various accelerators are indicated by horizontal bars. Sample configurations and their energy requirements are given below in Table 1.

A gun-type weapon, made with ^{233}U, requires 20 kg of fissile material, so the ordinate values on the left axis must be multiplied by 2.5. Note that subcritical-reactor transmuters cannot be directly used for ^{233}U production, so this conversion does not apply to the right axis. Hybrid transmuters can be used as neutron multipliers for ^{233}U production, but these are not reviewed here.[48]

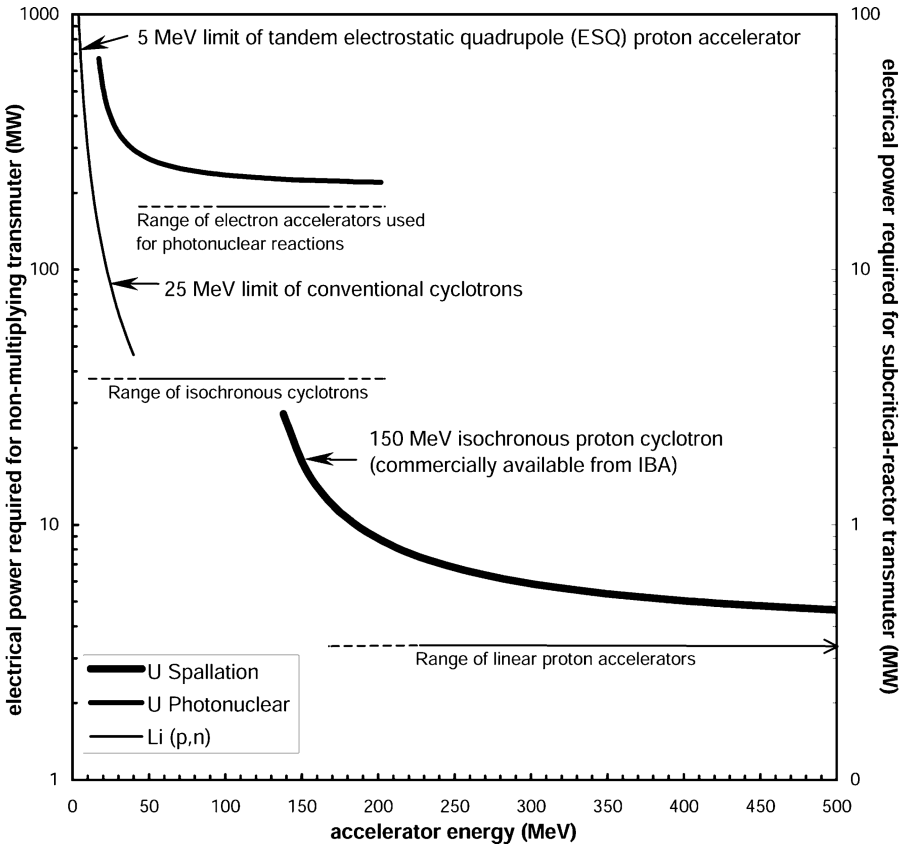

Figure 5: Compatibility and power requirements of various particle accelerators and neutron-production reactions.

REPROCESSING

Reprocessing is required to separate out freshly-produced fissile material from fertile material and waste products. The chemical processes used are thoroughly described in the open literature, and all materials are available on the open market. Several studies have attempted to gauge the level at which reprocessing becomes a barrier to proliferation. They concluded that it is an easy task, even for the entry-level proliferator.[49] For example, a 1996 Sandia National Laboratory report characterized it as "a relatively simple process that might be operated by an adversarial group in a makeshift or temporary facility."[50]

Some reservations about these claims are appropriate, given historical cases of countries engaging in their initial reprocessing efforts. China is one example. For more than 10 years, the Chinese pursued research on reprocessing techniques, including a small program on solvent-extraction methods begun

Table 1: Power requirements for 4 kg of fissile material per year (one 8-kg implosion-type bomb every two years)[1]

Sample configuration	Electrical power required	Electricity cost per 8-kg bomb
5 MeV Tandem ESQ Li (p,n) w/lead block	750 MW	$630 M
5 MeV Tandem ESQ Li (p, n) w/subcritical reactor	53 MW	$45 M
18 MeV IBA high-current cyclotron Li (p,n) w/lead block	135 MW	$110 M
18 MeV IBA high-current cyclotron Li (p,n) w/subcritical reactor	9.8 MW	$8.2 M
25 MeV conventional cyclotron Li (p,n) w/lead block	87 MW	$73 M
25 MeV conventional cyclotron Li (p,n) w/subcritical reactor	6.3 MW	$5.3 M
100 MeV Linear electron accelerator w/lead block	170 MW	$150 M
100 MeV Linear electron accelerator w/subcritical reactor	12 MW	$10 M
150 MeV IBA cyclotron U spallation w/lead block	18 MW	$15 M
150 MeV IBA cyclotron U spallation w/subcritical reactor	1.3 MW	$1.1 M
235 MeV accelerator U spallation w/lead block	7.2 MW	$6.1 M
235 MeV accelerator U spallation w/subcritical reactor	0.51 MW	$0.43 M

[1]Values calculated as shown in Note 31. Power is acquired from accelerator current requirements by multiplaying by the accelerator beam energy. Electricity cost is assumed to be $0.06/kWh. Other parameters as described in the next under the heading, "The particle accelerator."

after receiving U.S. technical publications detailing the technique. Shortly after China detonated its first nuclear weapon (made with enriched uranium), a decision was made to abandon research on alternate reprocessing technologies and fast track the construction of a demonstration facility employing U.S. solvent-extraction technology. Even from this point, it took one and a half years and two to three hundred technical staff (of whom 60 had extensive radiochemistry experience) to build a demonstration plant capable of 10 metric tons per year,[51] which for the BGRR-like reactor (122 MWd/tonne uranium burn-up) would yield one kilogram of plutonium per year.

Pilot reprocessing plants might have a capacity of about 10 to 60 metric tons per year. North Korea's small plant has a 110-tons-per-year capacity.[52]

Reprocessing Facilities for a Small Plutonium Production Reactor

The radioactivity of fuel discharged from a BGRR-like reactor is about one-sixth that of typical power reactor fuel, but still requires substantial shielding.[53] Typical pilot-plant sizes suggest that the 75 tons of fuel in the core of the BGRR-like reactor would take about one to three years to reprocess. The 1977 OTA report estimated a cost of $55 million (within a factor of two or so) for a U.S.-built, simple reprocessing plant designed for BGRR-like-reactor fuel.[54] This is four times more than the estimated cost of the reactor itself, and many times the electricity cost for most of the accelerator-driven configurations.

Reprocessing for an Accelerator-Driven System

The reprocessing burden for accelerator-driven systems depends principally on the transmuter used. Neutron-multiplying transmuters rely heavily on fissions, and thus have radioactivity levels similar to nuclear reactors. They will also tend to have similar loading sizes. The 8-ft, light-water-moderated subcritical reactor, used as an example throughout this article, holds 102 metric tonnes—about one-third more material than the BGRR-like reactor.

For systems that minimize fission, like the lead-block transmuter, the radioactivity can be reduced. As radiation shielding is often the largest cost item in a reprocessing plant,[55] and remote handling equipment and process automation a second major cost, reducing radioactivity would make reprocessing more affordable. Additionally, the loading of fertile material may be smaller than in a reactor or subcritical transmuter, reducing the amount of material to be reprocessed. Although fission-minimized accelerator-driven transmuters use more than an order of magnitude more electricity, greater electricity cost might be offset—partially or entirely—by reduced reprocessing cost.

DETECTION

The successful operation of a clandestine fissile-material program—be it a BGRR-like reactor or accelerator-based system—requires the proliferator to avoid actions that might lead to direct detection or inspection requests from the International Atomic Energy Agency (IAEA). Even if the proliferator operated under such constraints, there are technical mechanisms for remotely detecting signatures innate to fissile-material production. The fission process used to multiply neutrons inside a nuclear reactor or accelerator-driven subcritical-reactor-transmuter produces several such signatures: heat, radioactivity, and various fission products. However, for systems of the small sizes discussed here, there are no publicly known detection methods that would be reliably immune to simple countermeasures.

Heat emitted from a 25-MWt reactor is a fraction of that emitted by highly exothermic industrial facilities, such as an aluminum smelting plant.[56] It could thus be colocated and its emissions masked accordingly. Accelerator-driven systems (using either transmuter configuration) would produce heat in amounts nearly equal to the accelerator's electrical consumption. For seven of the above twelve sample configurations, this is less than a BGRR-like reactor.

Alpha, beta and most gamma radiation from fissions can be contained almost entirely by shielding for either technology. Practicable techniques for detecting high-energy gamma and neutrino radiation at significant distances are not known to exist.

Fission products—chemical elements produced when nuclei split during fission—are trapped within the fuel elements. Those in gaseous form, especially

the inert gases, can leak out in small amounts. Their release rate during reactor operation is typically less than one percent of the release rate during reprocessing—thus the detectability is limited not by reactor effluents, but by reprocessing effluents. However, for the fuel extracted from a small 25-MWt reactor, or accelerator transmuter, effluent levels would be sufficiently low that detection at meaningful distances is unlikely.[57]

Classic intelligence mechanisms are useful in the detection of nuclear facilities. Both satellite (or aerial) imagery and human intelligence sources have been used with great success to detect nuclear reactors in the past. In principle, the small size of a BGRR-like reactor, and its absence of externally-identifying marks, means the reactor could be more easily hidden from overhead imagery than most reactors. Similarly, accelerator-driven systems also lack particularly identifying marks, with the exception of any power-generation infrastructure, which might or might not be colocated. It should not be assumed, however, that an entry-level proliferator could successfully thwart the well-funded and experienced human-intelligence services available to large states.

Export controls are the final mechanism by which the international community seeks to prevent and discover nuclear proliferation. Though the nuclear-grade graphite in the BGRR-like reactor is listed as an export-controlled material, its indigenous production would circumvent any detection in this way. Accelerator technologies are even less prone to detection via export controls, as the relevant technologies are not presently included on any export-control list. The amended London Guidelines (Zangger list; also INFCIRC/254 Rev. 6, parts I and II) refer to accelerator technologies only as they apply to electromagnetic isotope separation and "pulsed electron sources" used in the x-raying of nuclear implosion tests. The Wassenaar Arrangement[58] refers to particle accelerators only in the context of directed-energy weapons (neutral-particle beams). None of the accelerators discussed in this article would be subject to these export controls. Compared to nuclear-grade graphite, particle accelerators are substantially more difficult to manufacture indigenously. As such, export controls have the potential to pose a larger barrier to proliferation via their control of accelerators than they presently do to proliferation via their control of nuclear reactors.

CONCLUSIONS

Accelerators are a viable route to acquiring fissile material, though their benefits are very situation specific. The more advanced accelerators considered here—linear proton accelerators or isochronous cyclotrons—are among the most economically attractive and provide for a project of manageable scale, as only a few machines would be required. However, it is argued that these

accelerators are probably more difficult to build than nuclear reactors. That said, commercial turn-key systems and various forms of foreign assistance can be readily acquired without notification of any regulatory body. Considering then the ease with which these advanced accelerators can be acquired from foreign sources, the reduced reprocessing complexity afforded by nonmultiplying transmuters, and the simplicity of constructing a ^{233}U gun-type weapon, one concludes that many of the natural barriers to proliferation can be lifted by employing particle accelerators, even for the most primitive of proliferators.

If export controls were implemented, the attraction of accelerators would be greatly diminished. Only in circumstances where a proliferator is not confident in his ability to construct or safely operate a nuclear reactor, but could manufacture an accelerator indigenously, could accelerators be considered as an obvious route. The more easily constructed accelerators—like conventional cyclotrons and electrostatic quadrupole (ESQ) accelerators—tend to consume large amounts of electricity and require large-scale projects consisting of scores or hundreds of machines. ESQs used for plutonium production provide a case scenario. For one bomb in two years, fifty 100-mA ESQs would be needed to drive a subcritical-reactor transmuter, and 750 would be needed for the nonmultiplying transmuter. Electricity cost per bomb would total $45 M and $630 M, respectively.

In conclusion, accelerator technology should be considered for internationally accepted export-control lists. Domestic legislation requiring private companies to notify regulatory bodies of any foreign contracts related to accelerators, or the export of accelerator-related technical knowledge, might also be useful. Early forms of such legislation have already emerged in the United States (10 CFR Part 810) restricting the transfer of accelerators and subcritical assemblies with the specific purpose of processing special nuclear materials. The IAEA is also expected to release a TECDOC that recommends that the Agency consider "regulations on the issue." Though these and future measures will not eliminate the threat of proliferation from particle accelerators, they can render the threat nearer to that from small nuclear reactors.

NOTES AND REFERENCES

1. A forthcoming IAEA Technical Document entitled, *Implications of Partitioning and Transmutation in Radioactive Waste Managment*, will recommend that regulations be issued regarding small acceletors as a potential proliferation source.

2. The scope of this article has been limited to technologically-unsophisticated proliferators as most aspirant nuclear-weapon states are of this category.

3. Plutonium with higher levels of ^{240}Pu can still be used in weapons, though more plutonium is then required.

4. Testing consumes a proliferator's stockpile of fissile material—an important consideration if the stockpile is small and production rates are low. If foreign intelligence

detects a nuclear test and it is clear that all the proliferator's fissile material was consumed in the test, or if the test is detected as a gross failure—and thus it is assumed the proliferator has been unsuccessful in designing a weapon—then in both cases the proliferator would have no effective nuclear deterrent and could invite preemptive foreign intervention.

5. ^{232}U is produced by (n,2n) reactions and requires neutrons with energies above about 600 keV.

6. For example, a 20-kg sphere of ^{233}U (about one notional gun-type bomb) contaminated with 1 ppm ^{232}U gives 50 mrem/hr (0.5 mSv/hr) at 0.5 meters, one year after reprocessing. The same sphere gives about 160 mrem/hr (1.6 mSv/hr) at peak intensity, about a decade after reprocessing. The prevailing standard for the maximum-allowed dose for radiation workers in the United States is 5 rem (50 mSv/hr) per year. Thus, for 1-year separated ^{233}U, a worker would be allowed 100 hours of exposure. Safety standards for aspirant nuclear weapon states might be substantially lower. See J. Kang., F. N. von Hippel, "U-232 and the Proliferation-Resistance of U-233 in Spent Fuel." *Science and Global Security* 9(1): 1–32, 8.

7. Ibid.

8. 180 MWt for ^{233}U compared to 14 MWt for plutonium at a rate of one bomb in two years and 80% duty cycle. This calculation compares the production rates required for producing one ^{233}U gun-type bomb to that for producing one plutonium implosion-type bomb in the same period of ^{232}Th is time. The Maxwell-average (at 0.0253 eV) neutron-capture cross-section (γ_c) for ^{232}This 6.5 barns, and for ^{238}U it is 2.4 barns. If seven percent of the fertile material converted is ^{232}Th, and 20 kg is required for a gun-type bomb compared to 8 kg for an implosion-type bomb, then the reactor size difference is approximately $(M_{c-gun}/M_{c-implosion})$ $(0.07\ \gamma_{c-Th232} + 0.98\gamma_{c-U238})/(0.07\ \gamma_{c-Th232})$.

9. See note 10.

10. This section draws heavily upon John R. Lamarsh, "Dedicated Facilities for the Production of Nuclear Weapons in Small and/or Developing Nations," Section VI-A of Appendix Volume II, Part Two to *Nuclear Proliferation and Safeguards*, June 1977, Congress of the United States, Office of Technology Assessment. NTIS order #PB-275843.

11. At 80-percent duty cycle. The reactor would produce about 9.2 kg if run without interruption. At a burn-up of 122 MWd/t, only 0.05% of the plutonium is of the 240 isotope. (Lamarsh, "Dedicated Facilities for the Production of Nuclear Weapons")

12. For a first-generation implosion-type bomb, 8 kg is assumed, which is the amount of plutonium defined by the IAEA as a Significant Quantity.

13. Lamarsh, "Dedicated Facilities for the Production of Nuclear Weapons."

14. Carbon sublimes at 3825°C and boron boils at 4000°C, at one atmosphere pressure (*CRC Handbook of Chemistry and Physics,* 82nd ed., 2001–2002), so reduction in boron levels also means less carbon produced per unit of energy and feed material. Ultragrade graphite (better than nuclear-grade) could also be made by the partial combustion of methane, the primary constituent of natural gas, which is practically free of boron and readily available worldwide.

15. Though the indigenous production of either moderator is possible, the technical challenges of designing, building, and operating a heavy-water reactor are altogether more formidable than for a graphite reactor. The graphite reactor is thus thought a more plausible route for an unsophisticated proliferator and selected here for comparison.

16. A 25-foot cube of graphite (some 700 metric tonnes) is more than is necessary for a 25-MWth reactor. A 21-foot cube (415 metric tonnes) would suffice, costing $3.8 million if produced from petroleum coke in oxygen-free ovens. See Note 17 regarding inflation adjustments.

17. Capital costs include labor costs for construction workers, but not design engineers and operators. All costs throughout this article are converted to 2003 dollars using the Producer Price Index as calculated at http://www.jsc.nasa.gov/bu2/inflation/ppi/inflatePPI.htm. See also http://www.bls.gov/ppi/home.htm.

18. Leading works on this topic are from C. Rubbia's group at CERN and Charles Bowman's group at Los Alamos. See, for example: C. Rubbia et al. (1995), "Conceptual Design of A Fast Neutron Operated High Power Energy Amplifier." European Organization for Nuclear Research (CERN) CERN/AT/95-44 (ET); Ch. D. Bowman, (1997) "Accelerator-driven Systems in Nuclear Energy; Role and Technical Approach," ADNA Corporation, Los Alamos, NM 87544, ADNA/97-013; Ch. D. Bowman (1998) "Accelerator-Driven Systems for Nuclear Waste Transmutation," *Ann. Rev. Nucl. Part. Sci.* 48: 505–506.

19. ^{233}U can be produced in target channels of a natural-uranium-powered reactor, as described in this article, but this requires a reactor about 13 times larger than what would be required for plutonium, and such reactors are more difficult to build and prone to early detection.

20. Though not every permutation will yield a neutron producing system. For example, electron accelerators cannot be used for spallation.

21. The primary isotope of natural lead is ^{208}Pb. It has an elastic-scattering cross-section that is nearly independent of energy, and also a very-low neutron-capture cross-section (about five orders of magnitude less than those of the relevant fertile materials) on account of its highly stable, "double-magic" nucleus.

22. "Experimental Verification of Neutron Phenomenology in Lead and Transmutation by Adiabatic Resonance Crossing in Accelerator Driven Systems: A Short Summary," 5 April 2000, CERN; SL-Note-2000-034 EET.

23. This is for neutrons characteristic of a 1-GeV spallation spectrum. Neutrons produced by lower-energy accelerators, like those more easily acquired by a proliferator, would be contained with even greater efficiency since fewer collisions are necessary to reach the fertile-material capture resonance region, and because lead's scattering cross-section is nearly energy independent. Fertile material added to the volume would capture neutrons, thus further reducing the neutron losses through the surface. (Ibid.)

24. Equation 1 from John R. Lamarsh, *Nuclear Reactor Theory*, Addison-Wesley (Reading, 1972).

25. Fertile material captures neutrons efficiently at resonance energies corresponding to excitation energy states of the bound nucleus. Absorption by fissile material is small because of a 1/v dependence of the fission cross-section which enables fertile material to absorb neutrons preferentially, provided neutron moderation is sufficiently slow. Neutrons can also be premoderated from high energies to the energies associated with the capture resonance region before being exposed to fertile material in order to avoid unwanted high-energy reactions, such as the (n,2n) reaction giving rise to ^{232}U, or the fission of fertile material.

26. For example, a light-water moderated 8-ft cubic pile (102-tonne natural-uranium loading) gives 13.8 captures per source neutron, where neutrons are produced by spallation using protons with energies between 150 MeV and 1 GeV. This configuration is used as the typical subcritical reactor for all examples presented henceforth. From: Christine D. Riendeau, David L. Moses, Arne P. Olson, "Proliferation Potential of Accelerator-Driven Systems: Feasibility Calculations," Oak Ridge National Laboratory, Y-12 Plant,

November 1998. Note: Riendeau et al., give Monte Carlo estimates for the plutonium-production capacity and neutron multiplication of various subcritical nuclear reactors built with non-nuclear-grade materials or loaded with unenriched uranium. The article does not, however, discuss accelerators, neutron-producing targets, manufacturing costs, reprocessing requirements, or give relative technical complexity estimates specific to technologically unsophisticated proliferators.

27. These are not described here because of their level of technical complexity. The principle is outlined in J. Galy, J. Magill, H. Van Dam, J. Valko, "A Neutron Booster for Spallation Sources—Application to Accelerator Driven Systems and Isotope Production," *Nuclear Instruments and Methods in Physics Research A*, 485 (2002): 739–752.

28. Heavier nuclei can be used, but protons give the best yield for the invested energy.

29. With density 19.04 g/cm^3. A natural-uranium metal target of equal density is expected to have a slightly improved yield.

30. This target approximates maximum neutron production for spallation. J. S. Gilmore, G. J. Russell, H. Robinson, and R. E. Prael, "Fertile-to-Fissile and Fission Measurements for Depleted Uranium and Thorium Bombarded by 800-MeV Protons," *Nuclear Science and Engineering*, 99 (1988): 41–52 in J. Magill and P. Peerani, "(Non-) Proliferation Aspects of Accelerator Driven Systems," *Journal de Physique IV*, France, 9 (1999). This paper restricts considerations to spallation-based neutron production and considers only transmuters made entirely of solid fertile material with no moderating material. The treatment of particle accelerators is primarily historical and not very relevant to the entry-level proliferator. The paper gives useful estimates of spontaneous neutron production from light isotope contamination, relevant to estimates of critical mass, and estimates radiation hazards arising from ^{232}U contamination in ^{233}U.

31. For example, if 4 kilograms of ^{239}Pu are desired per year (for one 8-kg bomb in two years), then 4 (kg/yr) $\div$ 0.239 (kg/g-mole) = 16.7 (g-mole/year); 16.7 (g-mole/year) $\times 6.02 \times 10^{23}$ (atom/g-mole) $= 1.01 \times 10^{25}$ (atom/year) are to be converted. Using Eqn. 2, a 235-MeV accelerator (commercially available) would produce $0.0367 \times (235–120) = 4.22$ (neutron/proton). Since one neutron is needed to convert one atom, assuming no losses, then 1.01×10^{25} (atom/year) $\times$ 1 (neutron/atom) $\div$ 4.22 (neutron/proton) $= 2.39 \times 10^{24}$ (proton/year), or 7.59×10^{16} (proton/second). Assuming an electrical efficiency of 50%, then 7.59×10^{16} (proton/second) $\times$ 1.60×10^{-19} (coulomb/proton) $\div$ 50%=2.43×10^{-2} (coulomb/second) = 24 mA.

32. In the 100–200 MeV region, Bremstrahlung photons have energies that interact with target nuclei through the Giant Dipole Resonance. Above these energies, Quasi-Deuteron, and Delta Resonance (pion-production) effects reduce the reaction efficiency. The threshold for removing one neutron is around 7–8 MeV. A. Fassò, A. Ferrai, P. R. Sala, "Designing Electron Accelerator Shielding with FLUKA," CERN [http://www.fluka.org/reference/papers/arlphnuc.ps.gz]; H. Nifenecker; S. David, J. M. Loiseaux, A. Giorni (December 1998) "Electron Induced Neutron Production," Hybrid Nuclear Reactors, Institut des Sciences Nucléaires, Grenoble. http://lpsc.in2p3.fr/gpr/PPNPport/node88.html

33. Equation derived from experimental data published in W. C. Barber and W.D. George, "Neutron Yields from Targets Bombarded by Electrons." *Phys. Rev.* 116 (1959): 1551–1559. Equation from trendline adjusted so that neutron yield at 100 MeV equals the average of the yield predicted by Barber and George and of the experimental yield of the GELINA facility's U-Mo target. The two sources agree within three percent. GELINA data from: M. Flaska1, D. Lathouwers, A. J. M. Plompen, W. Mondelaers, T. H. J. J. van der Hagen, H. van Dam, "GELINA Neutron Target Optimisation" European Commission Directorate-General Joint Research Centre, Belgium; and the Delft University of Technology, Mekelweg, Netherlands. http://www.itn.mces.pt/ICRS-RPS/oralpdf/Tuesday11/Session12_4/Plompen02.pdf.

34. Linear electron accelerators are less expensive than linear proton accelerators of comparable energy, owing to the fact that electrons reach relativistic speeds at much lower energies than protons. Brolly, Á, Vértes (2003). "Concept of a Small-Scale Accelerator Driven System for Nuclear Waste Transmutation," *Annals of Nuclear Energy*. Reactor Analysis Department, KFKI Atomic Energy Research Institute, Budapest.

35. Lithium-7 comprises 92.6 percent of natural lithium, and other isotopes do not need to be isotopically separated.

36. Equation derived by the author from experimental data published in K. Porges, J. L. Snelgrove, R. Gold, A. DeVolpi, R. J. Armani, and C. E. Cohn, "Thick Target Neutron Yields of Lithium and Beryllium Targets Bombarded with Protons and Deuterons," in *Applied Physics Division Annual Report July 1 1970 to June 30, 1971*, Argonne National Laboratory (IL, January 1972) Report ANL -7910, pp 361–362.

37. Prices given in U.S. dollars. $0.06/kWh is based on a worldwide average (giving equal weighting per country) of the minimum industrial energy price (not busbar costs) from the 9-year period 1994–2002. Prices were not adjusted for inflation over this period. The index excludes nuclear weapon states and members of the European Union. Data from the U.S. Department of Energy [available at http://www.eia.doe.gov/emeu/international/elecprii.html].

38. Based on General Electric LM6000 aeroderivative gas turbine generators, with 40 MWe capacity each, operating on natural gas. These and similar preengineered systems can be shipped immediately and operational within 3–4 months. Prices in U.S. dollars as quoted in July 2003 in *Power Generation Options for New Zealand*, a report prepared for Ministry of Economic Development by Sinclair Knight Merz Limited, Auckland, NZ [http://www.med.govt.nz/ers/electric/new-generation-options/skm/index.html]. Operating cost based on $20/Gcal of natural gas and at 40% efficiency. The resulting price per kWh, unlike the $0.06/kWh figure described in Note 37, does not include cost of maintenance, distribution, insurance, personnel, etc.

39. Estimated from a survey of cyclotrons.

40. A technique of vertically focusing the naturally-divergent beam of like-charged ions, correcting for defocusing caused by increases in the magnetic-field strength.

41. "The 88-Inch Sector-Focused Cyclotron," Lawrence Radiation Laboratory Publication #54, 1967. Updated and published online [at http://www.lbl.gov/nsd/user88/cycgreenbook.html].

42. Lamarsh, "Dedicated Facilities for the Production of Nuclear Weapons."

43. P. Cohilis, Y. Jongen, G. Lannoye, *Recent Advances in the Design of A Cyclotron-Driven Intense, Subcritical Neutron Source*, Ion Beam Applications, s.a., Belgium; and P. Cohilis, Y. Jongen, *High Beam Intensities for Cyclotron-Based Radioisotope Production*, Ion Beam Applications s.a., Belgium.

44. "Three Generations of Cyclotrons" adapted and updated from *The 88-Inch Sector-Focused Cyclotron,* 1967. [http://www.lbl.gov/nsd/user88/cycgreenbook.html].

45. See box, "History of Electronuclear Breeding."

46. Assumes 80% duty cycle, and a subcritical reactor with 13.8 neutron captures per source neutron.

47. The multiplying transmuter used for the chart gives 10 neutron captures per source neutron (not 13.8 as used elsewhere) owing to limitations of the graphing software.

48. For hybrid transmuters, see Note 27.

49. W. G. Sutcliffe and T. J. Trapp, Eds., *Extraction and Utility of Reactor-Grade Plutonium for Weapons (U)*, Lawrence Livermore National Laboratory, April 27, 1995; also Lamarsh, "Dedicated Facilities for the Production of Nuclear Weapons."

50. J. P. Hinton et al., *Proliferation Resistance of Fissile Material Disposition Program (FMDP) Plutonium Disposition Alternatives: Report of the Proliferation Vulnerability Red Team*, Sandia National Laboratories, Report no. SAND97-8201, October 1996, Section 4.1.1.3, pp 4.3–4.9. in V. Gilinsky, M. Miller, and H. Hubbard, *A Fresh Examination of the Proliferation Dangers of Light Water Reactors*, The Nonproliferation Policy Education Center. Estimates of the cost, personnel requirements and time were made in the above reports, and are also available from historical documents. Frequently cited is the design proposal for the Phillips plant, designed for fuel with a burn-up of 10,000 MWd/t. There are questions as to the accuracy of such estimates, as history indicates that reprocessing plants were often more expensive and complicated than such early designs estimated (Lamarsh, "Dedicated Facilities for the Production of Nuclear Weapons"). For information about the Phillips plant, see: H. Schneider et al., *A Study of the Feasibility of a Small Scale Reprocessing Plant for the Dresden Nuclear Power Station*, Report IDO-14521, Phillips Petroleum Company, April 28, 1961, available from the National Technical Information Service.

51. *Modern China's Nuclear Industry*, edited by the Dangdai Zhongguo [China Today] in Chinese. Selections translated and republished by the United States Joint Publications Research Service, 26 April 1988. JPRS-CST-88-008, pp. 11–19. Available from the National Technical Information Service.

52. Sharon A. Squassoni, *North Korea's Nuclear Weapons: How Soon an Arsenal?*, *Congressional Research Service Report*, Order Code RS21391, February 2, 2004 [http://fpc.state.gov/documents/organization/29649.pdf].

53. Assumes for the BGRR-like reactor at a burn-up of 122 MWd/tonne, 100% capacity factor, and a cooling period of 120 days that reduces the radioactivity by a factor of about 100 to 45,000 curies/tonne. This compares to 287,000 curies/tonne for fuel extracted from a 1 GWe light water reactor (LWR) operated at 33,000 MWd/t at 100% load factor, and a 10-year cooling period. BGRR data from Lamarsh, "Dedicated Facilities for the Production of Nuclear Weapons." LWR data from Anthony V. Nero, Jr., *A Guidebook to Nuclear Reactors*, University of California, 1979, pp 36–37.

54. Adjusted to 2003 U.S. dollars using the Producer Price Index.

55. Lamarsh, "Dedicated Facilities for the Production of Nuclear Weapons."

56. Aluminum smelting is one of the most energy-intensive industrial processes. Between 15 and 20 kWh/kg of aluminum is required. A typical smelting facility with 300 pots might produce 125,000 metric tonnes of aluminum per year; consuming about 280 MW of energy. Statistics from the International Aluminum Institute (http://www.world-aluminium.org/production/smelting/). This level of aluminum production is not unreasonable for small states. For example, Dubai Aluminum Co., United Arab Emirates, had a 536,000 tons per year capacity in 2002. The state-owned IRALCO in central Iran produces 120,000 tons of aluminum per year. ("A glance at the Aluminum Industry," *National Geoscience Database of Iran*, http://www.ngdir.ir/News/NewsReportDetail.asp?PId=55)

57. A study of ^{85}Kr—a commonly-considered inert gas effluent—considered the detection of India's Trombay reprocessing plant if it were to reprocess Hanford-reactor type fuel. Trombay has a 50 tonnes-heavy-metal per year capacity. This is a similar capacity to what might be used to reprocess the 75 tonnes of fuel from a BGRR-like reactor. Hanford-type fuel contains about 260 Ci/kg of ^{85}Kr, much less than the 53 Ci/kg in BGRR-like reactor fuel after one year of operation, so estimates of its detectability would be overstatements for our case. Even with the more radioactive Hanford

fuel, ^{85}Kr levels were predicted to drop below the natural background at distances greater than about 100 kilometers. Zia Mian and A. H. Nayyar, (2002) "An Initial Analysis of ^{85}Kr Production and Dispersion from Reprocessing in India and Pakistan." *Science and Global Security* 10 (3). For experimental results supporting this claim, see Martin B. Kalinowksi, *Measurements and Modelling of Atmospheric Krypton-85 as Indicator for Plutonium Separation*, IANUS, TH Darmstdat. [http://www.ianus.tu-darmstadt.de/Publikationen/Kalinowski/Kr-geel/kr-geel.html].

58. The Wassenaar Arrangement is a global multilateral arrangement on export controls for conventional weapons and sensitive dual-use goods and technologies. It received final approval from its 33 cofounding countries in July 1996 and began operations in September 1996 [see http://www.wassenaar.org].