THE ROLE OF URANIUM ENRICHMENT IN NUCLEAR PROLIFERATION AND POTENTIAL IMPLICATIONS FOR IRAN'S NUCLEAR PROGRAM

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ABSTRACT

This thesis assesses the uranium enrichment route and the plutonium production route for fissile material acquisition. The method to perform the analysis is a direct comparison of the uranium enrichment route and the plutonium production route across three dimensions: general factors, technology, and probability of detection using modern intelligence collection means. Three conclusions are derived from the analysis. First conclusion states that using uranium enrichment to produce fissile material requires less time, fewer steps, and is less expensive than using plutonium production to produce fissile material. Second conclusion indicates that technology availability and complexity have been the main barriers for states to acquire significant quantities of fissile material. Third conclusion identifies that the uranium enrichment route is less detectable than the plutonium production route by modern intelligence collection means. The conclusions derived from the analysis imply that if a state were to choose between uranium enrichment and plutonium production for fissile material acquisition today, it will likely choose the uranium enrichment because the technology has the same availability, but the route itself is shorter, cheaper, and less detectable by modern intelligence collection means. Policy recommendations are developed to ensure that in the light of the anticipated nuclear renaissance the proliferation of nuclear weapons using the uranium enrichment route are addressed properly.

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Chapter 1. Introduction

The focus of this paper is to assess the uranium enrichment and plutonium reprocessing routes for fissile material acquisition. The assessment is performed in three dimensions: general factors, technology, and probability of detection using modern intelligence collection means. The purpose of this paper is to understand the role of uranium enrichment and plutonium reprocessing routes for fissile material acquisition in the contemporary nonproliferation environment and to identify measures that have been effective in restaining or reversing uranium enrichment or plutonium reprocessing programs at different stages of their development.

Main question

This paper aims to answer two questions. What are opportunities for and constraints of the uranium enrichment and plutonium reprocessing routes for fissile material acquisition in the contemporary nonproliferation environment? What measures have effectively restrained or reversed proliferation of uranium enrichment or plutonium reprocessing programs at different stages of their development?

From the standpoint of nuclear weapons proliferation, the two most important parts of the nuclear fuel cycle are uranium enrichment and plutonium reprocessing.[1] A well-known fact that these technologies can be used both in nuclear power and nuclear weapons programs have raised the concerns of individual states and the international community as a whole since the introduction of nuclear power in the early 1950's.[2] Both uranium enrichment and plutonium reprocessing programs have continued to attract international attention in the recent past. North

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[1] Richard Kokoski, "Technology and Proliferation of Nuclear Weapons", SIPRI, Oxford University Press, 1995, p. 219, pp.2-3

[2] The "Atoms for Peace" speech that raised concerns at the international level was delivered by U.S. President Dwight D. Eisenhower to the UN General Assembly in New York City on December 8, 1953. Dwight D. Eisenhower Presidential Library.

Korea and Syria both pursued clandestine plutonium production routes.[3] And Libya and Iran have concealed the uranium enrichment projects.[4] While the international community has effectively forced Libya and Syria to abandon their nuclear weapons programs, it has not succeeded in reversing North Korea's nuclear weapons project.[5] The state of the atomic program in Iran and support it gets from domestic political elite indicates that Iran has both the capability and motivation to develop nuclear weapons despite continuous international pressure.[6]

The issue of spreading uranium enrichment and plutonium reprocessing technology becomes even more salient in the light of anticipated nuclear renaissance. According to the International Atomic Energy Agency (IAEA), over 40 states are seriously considering nuclear power as a sustainable source of energy.[7] The global nuclear marketplace is more active today than it has been in at least 20 years.[8] States in the Middle East, Latin America, Africa, and Southeast Asia have identified a desire to start or revive nuclear power programs. Many of these states are already receiving assistance from various suppliers.[9] If not addressed properly this expansion of nuclear power programs can have tremendous policy implications resulting in the renaissance of nuclear proliferation, not nuclear power. The efforts to expand the use of nuclear energy can result in spreading sensitive technology that states in changing strategic and domestic circumstances can choose to use to develop nuclear weapons.

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[3] Joseph Cirincione, Jon B. Wolfsthal, Miriam Rajkumar, "Deadly Arsenals: Nuclear, Biological and Chemical Threats," Washington, D.C.: Carnegie Endowment for International Peace, 2005, p.279.
[4] Ibid, pp. 295 and 317.
[5] T. Graham, K. A. Hansen, "Preventing catastrophe: The Use and Misuse of Intelligence in Efforts to Halt the Proliferation of Weapons of Mass Destruction", Stanford University Press, 2009, p.61-64, 162-163.
[6] Therese Delpech, "Iran and the Bomb", Columbia University Press, New York, 2007, pp.87-93.
[7] Ferenc L. Toth, Hans-Holger Rogner, "Prospects for Nuclear Energy in the 21st Century", International Atomic Energy Agency, Inderscience Enterprises, 2008, pp.1-2.
[8] Ibid, pp.3-27.
[9] Ibid, pp.162, 177, 204, 342.

By analyzing both the past and the current state of uranium enrichment and plutonium production routes for fissile material acquisition, this thesis aims to identify the loopholes in the contemporary nonproliferation environment that states desiring nuclear weapons capabilities can use to their advantage. By analyzing measures that individual states and the international community as a whole has applied to nuclear weapons programs of other states in the past, this paper aims to assess the effectiveness of different instruments to reverse or restrain states from developing or diverting into nuclear weapons programs. Based on the results of the analysis performed in this paper, policy recommendations are provided as to what actions can be utilized by the international community to assure and expand the peaceful use of nuclear energy in the light of anticipated nuclear renaissance. A separate assessment of the Iranian nuclear program is performed and policy recommendations are provided as to what instruments are most effective to prevent Iran from acquiring fissile material at the current stage of its nuclear program.

Original contribution

This thesis provides a direct comparison of uranium enrichment and plutonium production routes for fissile material acquisition across a broad set of factors. The factors are drawn from the most prominent work on uranium enrichment written by Allan S. Krass in 1983 and the work on plutonium production by Walter Patterson in 1984. This thesis extends the prominent work on the nuclear fuel cycle written by Robert G. Cochran and Nicholas Tsoulfanidis in 1993 by focusing on the availability of nuclear material and technology through trade in the contemporary nonproliferation environment.[10]

[10] Allan S. Krass, Peter Boksma, Boelie Elzen and Wim A. Smit, “Uranium enrichment and Nuclear Weapon Proliferation”, SIPRI, Taylor and Francis Ltd., London, 1983; Walter C. Patterson, “The plutonium business and the spread of the bomb”, San Francisco : Sierra Club Books, 1984; Robert G. Cochran and Nicholas Tsoulfanidis, “Nuclear Fuel Cycle: Analysis and Management”, American Nuclear Society, 2 Ed., 1993.

This thesis extends the proliferation debate beyond the question of how technology became available to states. Instead, it focuses on the questionof how technology acquisition methods evolved in response to measures implemented by individual countries and the international community to restrain technology proliferation. To perform the analysis, this thesis utilizes conclusions about the correlation between civilian nuclear cooperation and nuclear weapons acquisition done by Matthew Furhman and the effect of the illicit nuclear market on the nuclear weapons programs identified by Matthew Kroenig and David Albright.[11]

This thesis introduces technology complexity as another equally significant barrier for states to acquire fissile material. The aspect of mastering technology and the connection between the transition from laboratory-scale to pilot-scale to industrial-scale production of fissile material and the development of nuclear weapons programs has been only slightly analyzed in the literature. The data for the analysis are drawn from the work on technology proliferation trends written by M.D. Zentner, G.L. Coles, and R.J. Talbert in 2005 and the book about the connection between technology and nonproliferation written by Richard Kokoski in 1995.[12]

This thesis takes a broader look at different aspects of concealing the development of fissile material acquisition programs in the contemporary verification regime. The paper summarizes the main aspects of four different works in this area and provides overall conclusions which have not been done in any relevant literature so far. It uses Alexander Bollfrass's analysis which is limited to large-scale fissile material acquisition programs that

[11] Matthew Fuhrmann, "Spreading Temptation: Proliferation and Peaceful Nuclear Cooperation Agreements," International Security, Vol. 34, No.1 (Summer, 2009); Matthew Kroenig, "Importing the Bomb: Sensitive Nuclear Assistance and Nuclear Proliferation," Journal of Conflict Resolution, Vol. 53, No. 2 (April 2009); David Albright, "Peddling Peril: How the Secret Nuclear Trade Arms America", Free Press, 2010.

[12] M.D. Zentner, G.L. Coles, R.J. Talbert, "Nuclear Proliferation Technology Trend Analysis", Pacific Northwest National Laboratory, 2005; Richard Kokoski, "Technology and Proliferation of Nuclear Weapons", SIPRI, Oxford University Press, 1995.

involve interaction with foreign states.[13] It utilizes Bruce Larkin's analysis that concentrates on small-scale, distributed, and indigenous programs.[14] It also employs Joseph Rotblat's and Berhanykin Andemicael's assessment of general verification techniques for detecting clandestine uranium enrichment and plutonium production programs.[15]

This thesis expands the debate of the effectiveness of different policy instruments applied to reverse or restrain states from acquiring fissile material. It includes the assessment of how four policy measures have influenced the efforts of a state to acquire fissile material at three different stages of its nuclear program development. Policy measures analyzed in this paper include diplomatic pressure, sanctions, military options, and security assurance. The effectiveness of these instruments is assessed when applied to the laboratory-scale, pilot-scale and industrial-scale stages of a state's nuclear program development. Policy mechanisms assessed in this thesis are drawn from Kurt M. Campbell's book *Nuclear Tipping Point: Why states reconsider their nuclear choices* written in 2004.[16] Individual cases to support conclusions are drawn from Joseph Cirincione's book *Deadly Arsenals: Nuclear, Biological and Chemical Threats* written in 2005 and Frank Barnaby's book *How Nuclear Weapons Spread*, written in 1993.[17]

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[13] A. K. Bollfrass, B.M. Blechman, "Elements of a Nuclear Disarmament Treaty", Henry L. Stimson Center. Washington, DC, 2010.
[14] B. Larkin, "Designing Denuclearization", Transaction Publishers, New Brunswick, 2008.
[15] Berhanykin Andemicael and John Mathiason, "Eliminating Weapons of Mass Destruction: Prospects for Effective International Verification", Palgrave Macmillan, New York, 2005; Joseph Rotblat, "Nuclear Weapons: The Road to Zero", Westview Press, 1998.
[16] Kurt M. Campbell, Robert J. Einhorn, and Mitchell B. Reiss, "Nuclear Tipping Point: Why states reconsider their nuclear choices", Brookings Institution Press, Washington, DC, 2004.
[17] Joseph Cirincione, Jon B. Wolfsthal, Miriam Rajkumar, "Deadly Arsenals: Nuclear, Biological and Chemical Threats," Washington, D.C.: Carnegie Endowment for International Peace, 2005; F. Barnaby, "How Nuclear Weapons Spread", Routledge, London, 1993.

Methodology

This paper analyzes fissile material acquisition routes across a broad set of general factors, technology availability, and complexity as well as the probability of detection by modern intelligence collection means. These areas represent the most extensively discussed aspects of nuclear programs.[18] In both the technology and the detection realms, nation states have certain loopholes for acquiring nuclear weapons capabilities as analyzed in the relevant literature.[19]

The assessment of fissile material acquisition routes in the contemporary nonproliferation environment is done by developing four hypotheses. **Hypothesis 1** states that using uranium enrichment to produce fissile material requires less time, fewer steps, and is less expensive than using plutonium production to produce fissile material. The paper tests the hypothesis by assessing both the uranium enrichment route and the plutonium production route across a spectrum of factors. Primary factors include the amount of fissile material, the amount of natural uranium, number of nuclear facilities, and time and costs needed to build a nuclear weapon. Secondary factors assessed are requirements for special materials and related equipment or skills required to execute a fissile material acquisition route. The factors are drawn from literature explaining the peculiarities of uranium enrichment and plutonium production routes in great detail. The division into primary and secondary is done in a following manner. If a factor is absolutely required to execute either of the fissile material acquisition route, it is treated as primary. If a factor is necessary but not required it is identified as secondary.

The availability of technology through trade for either uranium enrichment or plutonium production route is assessed separately as a factor intervening into the process of fissile

[18] Such conclusion is made by analyzing the prominent works on nuclear programs used in this thesis. For instance, Allan S. Krass's book on uranium enrichment has three parts, one on uranium enrichment fundamentals, one on uranium enrichment principles and one on options for control. Same areas are covered in the Walter C. Patterson's book.
[19] Allan S. Krass, Peter Boksma, Boelie Elzen and Wim A. Smit, "Uranium enrichment and Nuclear Weapon Proliferation", SIPRI, Taylor and Francis Ltd., London, 1983, pp.207-210.

material acquisition using either uranium enrichment or plutonium production. Diversion of fissile material is analyzed across the same spectrum of factors as an alternative method for fissile material acquisition.

Hypothesis 2 states that technology availability and complexity have been the main barriers for states to acquire significant quantities of fissile material. The thesis tests this hypothesis by analyzing the main hurdles that nuclear weapons states with various program ranges have faced. It introduces four factors as such hurdles: technology availability, technology complexity, supply of natural uranium, and financial constraints. These four factors have been identified by the author of this research as consistent across all nuclear weapons programs regardless of their size. The paper treats a factor as a main barrier if a state failed to develop alternative solutions to progress with the development of its nuclear weapons program. A factor is treated as an alternative barrier if a state was able to find an alternative solution without significantly delaying its fissile material acquisition program.

The thesis starts testing the hypothesis by analyzing how technology availability factored in for states that developed nuclear weapons arsenals. It then assesses whether the methods developed to acquire weapons-related technology have provided states with alternative avenues to avoid hurdles with fissile material production programs. The paper next tests technology complexity factor by analyzing the time it took states to progress from laboratory-scale to pilot-scale to industrial-scale production of fissile material. Cases of states that failed to develop at least pilot-scale production are included to assess how complexity can prevent a state from acquiring significant quantities of fissile material. The thesis assesses the supply of natural uranium and financial constraints as alternative barriers to a nuclear weapons program's development. It does so by analyzing the alternative solutions states were able to develop in the past to remove these barriers on their way to acquiring large amounts of fissile material.

Hypothesis 3 states that the uranium enrichment route is less detectable than the plutonium production route by modern intelligence collection means. The thesis starts testing this hypothesis by analyzing nuclear facilities involved in the uranium enrichment and the plutonium production route. The degree of exposure of each type of nuclear facility varies depending on the activities performed inside a nuclear facility. These activities have been detected in the past using different intelligence collection means. Relevant cases of detection are assessed in order to compare the detection record for nuclear facilities involved in the uranium enrichment route and the plutonium production route.

The thesis further tests the hypothesis by assessing fissile material acquisition programs at large. Scale, time, and the origins of the programs are analyzed with respect to the probability of detection by modern intelligence collection means. In doing so, the thesis tries to resolve the debate in the conventional literature with regards to how the scale of a nuclear program and its origins correlate with the probability of detection.[20] The paper finishes testing the hypothesis by assessing the measures that states have used in the recent past to conceal either uranium enrichment or plutonium production programs. The understanding of the effectiveness of such measures provides guidance to what measures can be expected in the contemporary environment to produce fissile material using clandestine nuclear facilities. Verification of diversion of fissile material from civilian nuclear program is treated as an intervening variable. This part of the analysis intends to understand the possibilities and constraints of diverting fissile material from existing nuclear power program in order to avoid the need to construct clandestine facilities to produce fissile material.

[20] B. Larkin in his book “Designing Denuclearization” argues that a small-scale program can not escape detection, while A. K. Bollfrass, B.M. Blechman in the book “Elements of a Nuclear Disarmament Treaty” argue that only large-scale programs can be detected.

The assessment of the external instruments is done by developing **Hypothesis 4**. Different external measures have been effective in reversing or restraining a state's uranium enrichment or plutonium reprocessing program when applied to different stages of program development. The paper tests this hypothesis by analyzing four external measures that individual states or the international community at large applied to states developing nuclear capabilities in the past: diplomatic pressure, sanctions, military options, and security assurances. Both negative and positive measures are analyzed across a number of cases with uranium enrichment and plutonium reprocessing programs. External policy instruments that individual states or the international community applied to states that developed fissile material acquisition programs were drawn from the literature that specifically focused on cases of nuclear weapons programs reversals.[21] Both negative and positive measures are chosen for this analysis due to a significant difference in how states responded to different external measures applied to them depending on the scale of their fissile material acquisition program.

The paper assesses the factors that enabled or led to the failure of selected policy measures when applied to three different stages of a fissile material acquisition program development: laboratory-scale, pilot-scale, and industrial-scale. The stages are drawn from literature that analyzed technology proliferation trends. It concludes that a typical nuclear weapons program passes through three distinct stages in its development: laboratory efforts, pilot-scale production, and industrial-scale production.[22] Each stage of production is analyzed for factors that made states in the past less or more prone to submit to external pressure to reverse their nuclear weapons projects. Domestic factors that helped to restrain or reverse atomic weapons programs are treated as alternative variables.

[21] Kurt M. Campbell, Robert J. Einhorn, and Mitchell B. Reiss, "Nuclear Tipping Point: Why states reconsider their nuclear choices", Brookings Institution Press, Washington, DC, 2004.
[22] M.D. Zentner, G.L. Coles, R.J. Talbert, "Nuclear Proliferation Technology Trend Analysis", Pacific Northwest National Laboratory, 2005, p.31.

Roadmap

The organization of this paper is as follows. Chapter 1 explains the focus and the purpose of this thesis. It introduces the questions the paper aims to answer, their importance, and the place of this research in the current literature. It also explains the approach taken to complete the analysis and introduces the main hypotheses the analysis is organized around.

Chapter 2 test **Hypothesis 1** by analyzing the fissile material acquisition routes available to a state desiring nuclear weapons capabilities across a set of primary and secondary factors. The analysis performed in this chapter concludes that four out of five primary factors indicate the advantages of the uranium enrichment route of producing fissile material over the plutonium production route. These factors are the amount of natural the uranium available, steps of the nuclear fuel cycle, and time and costs required to execute a fissile material production route. Although the diversion route could initially appeal as a preferred route for fissile material acquisition because of its speed and low level of costs, however, the amount of material required to be diverted, the high visibility and the high degree of risk involved, all indicate that it may in fact not be the most practical route to take for a state that is interested in developing nuclear weapons.

Chapter 3 test **Hypothesis 2** by analyzing the barriers that states faced on the way to acquire significant quantities of fissile material. The analysis performed in this chapter concludes that technology availability and complexity have been the main barriers for states regardless of the size of their nuclear weapons programs. Enormous costs and long timelines for technology acquisition led many states that desired nuclear weapons capabilities to develop different routes to acquire necessary technology. The analysis performed in this chapter indicates that three forms of technology acquisition have been used in the past: direct purchase, civilian nuclear cooperation, and illicit nuclear marketing. Moreover, the methods of technology acquisition evolved along with the measures that individual states and the international community at large implemented to restrain technology proliferation.

Chapter 4 test **Hypothesis 3** by analyzing the uranium enrichment and the plutonium production routes in terms of probability of detection by modern intelligence collection disciplines. The analysis performed in this chapter concludes that the uranium enrichment route that utilizes gas centrifuge technology has a better chance of concealing its development than the plutonium reprocessing route. It also points out that the probability of detection of both the uranium enrichment and the plutonium reprocessing routes has positive correlation with scale, time, and the origins of the fissile material acquisition program. States in the past have used a number of techniques to conceal the development of their programs. The analysis illustrates that efforts to conceal the uranium enrichment facilities have been mixed, while attempts to conceal the plutonium reprocessing facilities have failed.

Chapter 5 test **Hypothesis 4** by analyzing policy instruments that were applied by the international community to reverse or restrain a state's uranium enrichment or plutonium production program. It assesses four types of external measures: diplomatic pressure, sanctions, military options, and a security assurance. The analysis performed in this chapter concludes that diplomatic pressure has been generally effective in restraining the laboratory-scale effort. Sanctions have a mixed record of success when applied to different stages of the development of a fissile material acquisition program. Military options have been successfully used to deny states of nuclear weapons programs at laboratory and pilot-scale stages. Security assurances worked to restrain a state that acquired industrial scale capacity to produce fissile material from actually developing a nuclear arsenal.

Chapter 6 provides policy implications as to how the current structure of the nonproliferation regime allows the states desiring nuclear weapons capabilities to procure nuclear fuel, material, and expertise. This chapter explains that the uranium enrichment will likely to be a proliferation route of choice in the contemporary nonproliferation environment. It also provides implications as to why states are likely to continue to exploit loopholes in current verification system to develop clandestine nuclear facilities Based on policy implication, the chapter suggests four policy recommendations as to what measures the international community can take to close existing loopholes and assure the secure use of nuclear energy. They include: involving the IAEA at the early stages of planning nuclear infrastructure, incorporating intelligence support into current verification regime, expanding the scope and the time frame for on-site inspections, and establishing regional and international uranium enrichment centers.

Separate policy implications and policy recommendations are provided for the Iranian nuclear program. Based on the analysis, this chapter implies that sanctions will not likely restrain Iran from developing an industrial-scale capacity for fissile material acquisition. Based on this policy implication, this chapter suggests that the optimal strategy for the United States and the international community at large to restrain Iran from acquiring fissile material programs is to provide the time necessary for Iran's proliferation motivations to change as well as simultaneously address its security threats and provide Iran with alternative avenues through which to acquire international prestige.

Chapter 2. The analysis of fissile material acquisition routes

This chapter tests **Hypothesis 1**. Using uranium enrichment to produce fissile material requires less time, fewer steps, and is less expensive than using plutonium production to acquire fissile material. In order to test the hypothesis this chapter analyzes the routes for fissile material acquisition across a broad set of factors. The factors used in this research are drawn from authors who analyzed the uranium enrichment route in great detail, the plutonium production route in great detail, as well as from authors who thoroughly described the complete nuclear fuel cycle.[23] A particular factor was selected only if its importance was highlighted by all authors.

The factors are divided by the author of this research into primary and secondary: the assessment, however, is performed across all factors to avoid bias. The division into primary and secondary is done in a following manner. If a factor is required to execute either uranium enrichment or plutonium production route it is treated as primary. If a factor is necessary but not required it is identified as secondary.

Primary factors include the amount of fissile material, the amount of natural uranium, steps of nuclear fuel cycle, and the time and costs needed to build a nuclear weapon. Secondary factors assessed are requirements for special materials and nuclear facilities. Different authors weigh various primary factors differently in their relation to either the uranium enrichment or the plutonium production programs, but most agree on those five to influence the fissile material acquisition program most. The analysis concludes that four out of five primary factors indicate the advantage of the uranium enrichment route of producing fissile material over the plutonium production route.

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[23] Allan S. Krass's work was used for assessing the uranium enrichment route, Walter Patterson's work was used to assess the plutonium production route and Robert G. Cochran's work was used to assess the complete nuclear fuel cycle.

A separate assessment of each fissile material acquisition route is performed for material and technology availability through trade. This is done for two reasons. First, the assessment sets the stage for the analysis in subsequent chapters. Second, it allows identifying what material and technology is traded without any monitoring by the international community. In fact, the analysis concludes that trade in critical technology for both the uranium enrichment and the plutonium reprocessing route is closely guarded by national and international agencies. Trade in natural uranium is, on the contrary, is not directly monitored by the international community and is based mainly on bilateral agreements between suppliers and recipients.

The analysis performed in this chapter concludes that a fissile material production route is technically complex, expensive, and a time-consuming endeavor. The acquisition of fissile material through diversion offers an alternative route to fissile material acquisition. Although the diversion route could initially appeal as a preferred route because of its speed and low level of costs, the amount of material required to be diverted, the high visibility and the high degree of risk involved, indicate that such route may not be the most practical one for a state to use to develop its nuclear weapons program. The summary of findings is presented in Table 1.

Table 1. Comparison of fissile material acquisition routes[24]

Factor	Fissile Material Production		The diversion route
	The uranium enrichment route	The plutonium production route	
Fissile material required, kg	25–60	6–75	6–75
Natural the uranium required, tons	4.5–11	30–200	4.5-30
Other special materials	No	Special purity graphite	None

[24] Sourcing for figures in Table 1 is provided in section that assess each individual factors.

required		or heavy-water	
Number of steps required to produce fissile material	3	4–5	0
Facilities required	Enrichment plant	Nuclear reactor and reprocessing facility	May require reprocessing facility
Time required	From several weeks to several years	Several years	From several months to several years
Cost involved, million USD	2–5	100–300	5-10 if a reprocessing facility is needed
Other factors	None	Handling of high levels of radioactivity is involved	High-risk, high-visibility operation

Uranium enrichment is a direct path to fissile material acquisition while plutonium production requires an additional step

Fissile material—highly enriched uranium (HEU) or plutonium—is used in a nuclear weapon.[25] There are two mechanisms by which natural uranium is converted to fissile material: through isotopic enrichment or transformation to plutonium.[26] The uranium mining is an indispensable starting point for the production of any fissile material.[27] Depending on the mechanism chosen to transform non-fissile material into fissile material only certain steps of a nuclear fuel cycle have to be executed. If the uranium enrichment route is chosen only three

[25] Depending upon the isotopic composition different amount of fissile material is required to produce a nuclear weapon. See Table 1 in Appendix A for comparison between amounts of HEU and plutonium required to assemble a nuclear weapon.

[26] Robert G. Cochran and Nicholas Tsoulfanidis, "Nuclear Fuel Cycle: The analysis and Management", American Nuclear Society, 2 Ed., 1993, pp.10-12.

[27] Uranium (especially its isotopes ^{235}U and ^{238}U) is the only naturally occurring fissile material. Plutonium is a product of transmutation of ^{238}U through irradiation of nuclear fuel in a nuclear reactor.

steps are required; in case of plutonium all steps of the nuclear fuel cycle have to be completed.[28]

The element uranium is very widely distributed; it is a metal approximately as common as tin or zinc, and it is a constituent of most rocks and even of the sea. In the process of extraction and purification, uranium is converted first to an oxide form U_3O_8 and then if enrichment is going to be performed to a solid hexafluoride form UF_6.[29] Unlike uranium, plutonium is not present in the Earth's crust, and has to be produced through irradiation of the uranium fuel in nuclear reactors. Natural uranium can be supplied only to production reactors (gas-graphite) and heavy-water reactors; other types of nuclear reactors require a supply of enriched uranium fuel.[30]

Uranium enrichment route requires less natural uranium, smaller budget and shorter timeline to develop than the plutonium production route

Natural uranium requirements

Produced or procured natural uranium in its oxide form or solid hexafluoride form cannot be used in a core of a nuclear weapon; it requires enrichment or irradiation. Any uranium enrichment method involves separating molecules of the uranium hexafluoride UF_6 containing ^{235}U from those containing ^{238}U. HEU for weapon purposes is the uranium enriched to more than 90 percent ^{235}U. It requires 4.5–11 tons of natural uranium to produce HEU required to assemble a nuclear weapon.[31] Currently, world prices for UF_6, the cost of natural uranium, and

[28] Ibid, pp.14-17.
[29] Robert G. Cochran and Nicholas Tsoulfanidis, "Nuclear Fuel Cycle: The analysis and Management", American Nuclear Society, 2 Ed., 1993, pp.25-26.
[30] Walter C. Patterson, "The plutonium business and the spread of the bomb", San Francisco : Sierra Club Books, 1984, p. 12.
[31] It requires 25 kg of HEU to build a nuclear weapon of an implosion design and 60 kg of HEU to produce a nuclear weapon of gun-type device. A simple formula is used to estimate the amount of natural uranium required to produce a 1 kg of HEU: 1 kg HEU (93% ^{235}U)=(ER-EN)/(EN-ET), where ER – required level of enrichment (0.93), EN – enrichment level of ^{235}U in natural uranium (0.0071) and ET – enrichment of ^{235}U in the tail (0.002).

the quantity required to produce a single nuclear weapon will range from $0.5 to $1.2 million per device, depending on the design.[32]

Natural uranium can be irradiated in any type of nuclear reactor. Depending on the type of a reactor, however, obtained plutonium material becomes more or less suitable for weapons production.[33] Production (gas-graphite), heavy-water or research reactors are better suited to irradiate nuclear fuel to produce the plutonium of weapons-grade level than power reactors. It must be emphasized, however, that it is possible to build a nuclear weapon using any reactor-grade plutonium. In 1962, the United States successfully tested a nuclear weapon from the plutonium extracted from an irradiated power reactor fuel.[34] Requirements for natural uranium range from 30 to 200 tons depending on the type of a reactor.[35]

Cost of production and timeline for acquiring fissile material

Separative work unit (SWU) is a single measurement that is used to estimate time, cost, and complexity of the uranium enrichment process. SWU allows assessing enrichment technology across the following elements: separation factor, throughput, energy requirements, capital, and operating costs. It takes 6000–14.500 SWU to produce HEU required to assemble a nuclear weapon.[36] Several generations of isotope separation machines have been developed;

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[32] World prices for UF6 can be monitored using the UXC website at http://www.uxc.com/review/uxc_Prices.aspx.

[33] The difference is in amount of plutonium required for a nuclear weapon and the predictability of a nuclear weapon. For weapons purposes it is more efficient to maximize the percentage of ^{239}Pu and minimize the percentage of other isotopes to keep the critical mass and radioactivity low and avoid pre-initiation of a nuclear weapon.

[34] J. Carson Mark, "Reactor-grade plutonium explosive properties", Nuclear Control Institute, Washington, DC, 1990, p.133.

[35] Robert G. Cochran and Nicholas Tsoulfanidis, "Nuclear Fuel Cycle: The analysis and Management", American Nuclear Society, 2 Ed., 1993, pp.20-21.

[36] SWU is calculated for a nuclear weapon of implosion design and for a nuclear weapon of gun-type design. The concept of SWU is explained in great detail in Allan S. Krass, Peter Boksma, Boelie Elzen and Wim A. Smit, "Uranium enrichment and Nuclear Weapon Proliferation", SIPRI, Taylor and Francis Ltd., London, 1983, pp.97-99.

their SWU capacity ranges from 1–50 SWU/year.[37] Depending on the type and number of isotope separation machines used, the timeline for producing the required amount of HEU varies from several weeks to several years.[38] Currently, at world prices for SWU, the cost of enriching uranium to produce a single nuclear weapon will range from $1.5 to $3.5 million per device, depending on the design.[39]

A single rule is used to estimate the speed of the plutonium production in almost any kind of nuclear reactor—the plutonium is produced at a rate of approximately 1 gram per day per megawatt-thermal (MWth) of reactor power.[40] A typical 100 MWth production reactor produces an equivalent of weapons-grade plutonium enough to build 5–6 nuclear weapons of implosion design in a year. It requires around 200 tons of natural uranium fuel, several years, and capital investments of $40–$60 million to put such reactor into operation.[41] A typical 1000 MWth power reactor produces an equivalent of reactor-grade plutonium enough to build 17 nuclear weapons of implosion design per year. It requires around 40 tons of enriched uranium fuel, 7–10 years, and capital investments of $3–5 billion dollars to construct a power reactor.[42]

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[37] Characteristics of isotope machines are explained in great detail by Alexander Glazer in his work "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation", Routledge, Taylor and Francis Group, Science and Global Security, 16:1-25, 2008, pp.8-11.

[38] Estimation is made for isotope separation machines of P-1 through P-5 designs. Ibid, pp.8-11.

[39] World prices for SWU can be monitored using the UXC website at http://www.uxc.com/review/uxc_Prices.aspx.

[40] Richard Kokoski, "Technology and Proliferation of Nuclear Weapons", SIPRI, Oxford University Press, 1995, p.75.

[41] Estimation is done for a research reactor comparable in MWth with a production reactor. Data is taken from Nuclear Research Reactors in the World database at IAEA website: http://www.iaea.org/worldatom/rrdb/.

[42] It is important to remember that it requires more reactor-grade plutonium than weapons-grade plutonium to build a nuclear weapon. Data for costs and timelines for construction is taken from World Nuclear Association website at http://www.world-nuclear.org/info/inf02.html.

Uranium enrichment route does not require handling high levels of radioactivity involved in the plutonium production route

Nuclear fuel irradiated in a nuclear reactor contains various highly radioactive isotopes and is consequently stored after extraction from the reactor for several months before it can be dissolved and reprocessed to separate the plutonium from other isotopes. After storage the irradiated fuel is sent to a heavily shielded chemical reprocessing facility where the plutonium is separated from uranium, transuranic elements, and fission products. All of these processes generate large quantities of highly-radioactive nuclear and chemical waste. The method of chemical reprocessing is simple, but it requires equipment that can handle high levels of radioactivity.[43] At the same time the uranium in both metal and gas forms in not highly radioactive substance and is handled without special equipment. Isotope separation machines and the materials produced from have strict requirements for handling corrosion but not radioactivity.[44]

Technology availability is a major intervening factor for both uranium enrichment and plutonium production routes

Technology and supply of natural uranium are critical to the development of the uranium enrichment route and the plutonium production route.[45] The analysis indicates that trade in technology for either uranium enrichment or plutonium production is regulated and closely guarded by the International Atomic Energy Agency (IAEA), while trade in natural uranium is not. This implies that if a state is able to procure necessary technology using alternative acquisition routes, it can supply its fissile material production program rather easily. At the same

[43] Walter C. Patterson, "The plutonium business and the spread of the bomb", San Francisco : Sierra Club Books, 1984, pp. 42-51.
[44] Allan S. Krass, Peter Boksma, Boelie Elzen and Wim A. Smit, "Uranium enrichment and Nuclear Weapon Proliferation", SIPRI, Taylor and Francis Ltd., London, 1983, pp.120-140.
[45] This is in depth analyzed in Chapter 2.

time, without the technology, a state can not acquire fissile material through production; its options are limited to purchasing or stealing fissile material.[46]

Trade in natural uranium is not regulated by the IAEA and is largely a product of bilateral agreements between a supplier and a recipient.[47] At the same time, major suppliers have an obligation under the terms of the London Supplier Group to notify the IAEA of transfers of "source and special materials," and to put them under IAEA safeguards if possible, and if not, then arrange secure storage of these materials at the recipient site.[48]

There are about 25 potential processes for enriching uranium but gaseous diffusion and gas-centrifuge processes are the most commonly used in the commercial market.[49] Trade in the uranium enrichment technology, including expertise, components, and materials is monitored by a number of national and international intelligence agencies. Certain aspects of this technology remain highly classified and closely guarded. The only de-classified enrichment technology that was used to produce a nuclear weapon is electro-magnetic isotope separation technology, which is extremely expensive and difficult to operate.[50]

Unlike enrichment technology—most of which remains highly classified—details of reprocessing technology are developed and well-known, although much of the equipment

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[46] The is no record of any state selling fissile material to another states. Advantages and disadvantages of theft of fissile material are discussed in the next section.

[47] Current price is 88USD/kg for U_3O_8 and 114USD/kg for UF_6)Prices are taken from the WNA website at http://www.world-nuclear.org/info/default.aspx?id=442&terms=uranium+prices.

[48] These guidelines are known as London Supplier Guidelines and they are published in the IAEA INFCIRC/254 of February 1978.

[49] Uranium enrichment technology is explained in great detail in Allan S. Krass, Peter Boksma, Boelie Elzen and Wim A. Smit, "Uranium enrichment and Nuclear Weapon Proliferation", SIPRI, Taylor and Francis Ltd., London, 1983, pp.120-190.

[50]Berhanykin Andemicael and John Mathiason, "Eliminating Weapons of Mass Destruction: Prospects for Effective International Verification", Palgrave Macmillan, New York, 2005, pp.87-90.

needed to deal with the high levels of radioactivity is under international control.[51] Reactor technology is also well-understood and developed.[52] Trade in reactor technology as well as critical materials, such as special purity graphite, heavy-water or enriched fuel, is based on bilateral agreements between supplier state and recipient state and is monitored and safeguarded by the IAEA.[53]

Theft of fissile material as an alternative method of acquisition is unlikely to be performed by a state due to its high visibility

The diversion of fissile material from a military program allows obtaining fissile material suitable for building a nuclear weapon. Despite its attractiveness, this route of acquisition involves a high degree of risk and visibility due to the safeguards on military programs. There is no record of even a limited amount of highly enriched uranium or weapons-grade being acquired by a state's nuclear weapons program.[54]

The diversion of fissile material from a civilian nuclear program can occur through theft of spent fuel or theft of fresh highly enriched research reactor or High Temperature Gas Reactor (HTGR) fuel. In order for spent fuel to be the source of fissile material, chemical reprocessing would be required to recover weapons-grade plutonium.[55] Several measures have been implemented to make access to reactor-produced fuel more difficult. These include spiking (irradiation or the addition of highly radioactive material which makes the irradiated nuclear fuel

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[51] The first detail revelations of this technology were made at the Geneva Summit Conference in 1955. D. Fisher, "Stopping the Spread of Nuclear Weapons: The Past and the Prospects", Routledge, London, 1992, p.40.

[52] M.D. Zentner, G.L. Coles, R.J. Talbert, "Nuclear Proliferation Technology Trend Analysis", Pacific Northwest National Laboratory, 2005, p.112.

[53] Walter C. Patterson, "The plutonium business and the spread of the bomb", San Francisco : Sierra Club Books, 1984, pp. 35-37.

[54] Careful studies of nuclear weapons programs by states that tested a nuclear device indicate no such evidence. It is reasonable to assume that it was either impossible to conduct such activity or unlikely to help advance atomic projects in a substantial manner.

[55] Atlantic Council's Nuclear Fuels Policy Working Group, "Nuclear Power and Nuclear Weapons Proliferation", Volume II, Westview Press, Colorado, 1977, Appendix A, p.19.

too dangerous to approach without special precaution), denaturing (dilution of fissile material with non-fissile materials which would require isotopic enrichment to extract) and physical protection (armed protection of facilities and irradiated nuclear fuel). The diversion of HTGR fresh fuel would similarly require chemical processing to recover the enriched the uranium.

Summarizing, the diversion route could initially appeal as a preferred route because of its speed and low level of costs. The amount of material required to be diverted, the high visibility, and the high degree of risk involved, however, represent low benefit approach for a state desiring nuclear weapons capabilities.

Chapter 3. Technology and fissile material acquisition

Chapter 2 concludes that using the uranium enrichment to produce fissile material requires less time, fewer steps, and is less expensive than using the plutonium reprocessing to produce fissile material. The purpose of this chapter is to test **Hypothesis 2**. Technology availability and complexity have been the main barriers for states to acquire significant quantities of fissile material.

The analysis indicates that four factors have been identified in the past as the hurdles for states to acquire large amounts of fissile material. They are the availability of technology, the complexity of technology, the supply of natural uranium and financial constraints. All four factors have been the barriers for all ten states that developed nuclear arsenals. All four factors have been consistent as problems for two states that have a large-scale nuclear arsenal (more than 1000 nuclear weapons), for three states that have a medium-scale nuclear arsenal (more than 100 weapons), and for remaining five states that either have or had a small-scale nuclear arsenal (less than 100 nuclear weapons). The division of nuclear weapons arsenals into large, medium and small is used solely for the purpose of differentiating nuclear weapons programs of nuclear weapons states.

The analysis further indicates that only two factors can be treated as the main barriers that either prevented states from acquiring large amounts of fissile material or significantly delayed nuclear weapons programs. They are the availability and the complexity of technology. The assessment conducted in this chapter indicates that states in the past have been able to develop alternative solutions to work around the supply of natural uranium and the financial constraints barriers, while alternative solutions to remove technology-related barriers have failed to succeed.

Technology availability as the first main barrier to acquiring fissile material

Six out of nine states that acquired nuclear weapons capabilities pursued both uranium enrichment and plutonium reprocessing routes to acquire fissile material. Three remaining states have either considered or tried to execute both routes but managed to accomplish only one of them.[56]

Table 2. Routes used to produce fissile material

Route	Country
Enrichment-diffusion	China, France, UK, US, USSR
Enrichment-centrifuge	China, India, Pakistan, South Africa, USSR
The uranium enrichment route total:	**8**
Production reactor	China, France, UK, US, USSR
Research reactor	India, Israel, North Korea
The plutonium route total:	**8**

The analysis of these nuclear weapons programs indicates that large-scale and medium-scale programs managed to develop both uranium enrichment and plutonium production technologies. The analysis of small-scale nuclear programs of states that built nuclear weapons arsenals illustrates that an arsenal was developed using the technology available at hand.

Small-scale programs, like the Indian, Israeli, Pakistani, or South African projects indicate that countries with considerably smaller defense budgets have analyzed and tried to execute both routes for acquiring fissile material but succeeded in one they had technology for. Both Israel and India purchased the plutonium production technology from capable suppliers in

[56] This conclusion is the result of the assessment of technology used for nuclear weapons acquisition explained in great detail in M.D. Zentner, G.L. Coles, R.J. Talbert, “Nuclear Proliferation Technology Trend Analysis”, Pacific Northwest National Laboratory, 2005.

the 1950's and 1960's. In 1956, France agreed to sell the Dimona reactor along with reprocessing technology to Israel.[57] In 1960 Canada and the United Sates supplied India with a heavy-water reactor.[58]

The decision to develop nuclear weapons arsenal using plutonium, however, came in both cases after thorough evaluation of the uranium enrichment options available to both states at the time. According to Fuad Jabber, Israel declined the gaseous centrifuge technology and electro-magnetic separation technology based on power requirements alone. He notes that the evaluation conducted by the Israeli government concluded that:

"a gaseous diffusion plant tailored to Israel's needs would certainly be much smaller than the American ones, but this would not render the task substantially easier, as it has been found that the simplest possible design of a gas-diffusion consists of such a great number of individual high-grade components that high initial capital investments for even a minimum size installations are unavoidable." [59]

India started scientific experiments with uranium only in 1967, by which time plutonium reprocessing technology was mastered at the laboratory-scale production efforts. [60] Frank Barnaby estimated, however, that both Israel and India revisited the uranium enrichment option later in the course of the development of their nuclear weapons programs.[61]

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[57] D. Fisher, "Stopping the Spread of Nuclear Weapons: The Past and the Prospects", Routledge, London, 1992, p.50

[58] F. Barnaby, "How Nuclear Weapons Spread", Routledge, London, 1993, p.71.

[59] Fuad Jabber, "Israel and Nuclear Weapons: Present Options and Future Strategies", London, Chatto and Windus, 1971, p.74.

[60] Brahma Chellaney, "South Asia's Passage to Nuclear Power," International Security, Vol. 16, No. 1 (Summer 1991), pp. 43—72.

[61] F. Barnaby, "How Nuclear Weapons Spread", Routledge, London, 1993, p.84-85 for Israel case and p.69 for India's case.

Pakistan initiated its nuclear weapons program in 1972 and initially followed the plutonium route.[62] However, the United States blocked Pakistan's purchase of a plutonium reprocessing plant from France.[63] In 1975 Dr. Abdul Qadeer Khan stole centrifuge enrichment technology from a subcontractor of URENCO in the Netherlands, where he had worked for several years, brought it to Pakistan, and with government backing, built a pilot-scale uranium enrichment facility at Kahuta (5.000 SWU/year) near Islamabad.[64] Pakistan also developed the plutonium reprocessing facility later on in the course of the development of its nuclear weapons program. [65] South Africa is probably the only exception to this rule. Due to large reserves of the uranium and developed mining and metallurgic industries, South Africa purposefully proceeded along the uranium enrichment route for fissile material acquisition. One can argue that the revelation of preparations for the nuclear test site by a Soviet satellite in 1977 could have influenced South Africa's decision to pursue uranium enrichment, which it concealed with great effort. [66]

Another factor that illustrates that technology was critical to both large-scale and small-scale programs is the percentage of nuclear weapons programs budgets spent on technology development. Research in technology, and development of industrial-scale fissile material production facilities constituted approximately 50 percent of expenditures in the atomic projects both in the United States and the Soviet Union. For the U.S. project, these sums vary from 100 million to 200 million dollars a year in 1947 dollars in the period from 1943 to 1953. For instance, in 1950, the United States spent 28.9 million dollars for research in chemistry, metallurgy, and

[62] Ibid, p.75.
[63] Ibid, p.77.
[64] Ibid, p.77.
[65] Ibid, pp.77-78
[66] Ibid, pp.111-112.

physics alone and almost an equal amount (31.5 million) for development of nuclear reactors.[67] Soviet archival documents indicate that the total cost of the Soviet atomic project in the period from 1949 to 1954 was around 20 billion rubles (in 1950 the ratio was 5 rubles to 1 dollar) out of which 20 percent was dedicated to research in dozens of areas of physics, chemistry, metallurgy, and so on.[68]

The role of technology and hardships with its acquisition were acknowledged by heads of atomic projects in the past. For example, the head of the Soviet atomic project Igor Kurchatov wrote in his memoirs that despite the fact that the Soviet atomic energy project was assigned top national priority, which meant that every scarce resource available was put at its disposal, two main obstacles were constantly slowing down the program: lack of industrial capacity and slow progress in scientific research.[69] The new field of science required solutions that had to be developed for the first time at the level of quality never reached before. New machinery as well as new processes, such as quality control had to be developed from scratch. Overall, the scope of the areas that required scientific research was enormous. Due to the sensitive nature of some of these areas, such as describing and solving chain reaction processes, extensive mathematical research was performed before experiments could proceed. [70]

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[67] Data is taken for years 1943-1953 for U.S. project. Sources: Richard G. Hewlett, Francis Ducan, "The New World: A History of the United States Atomic Energy Commission", Vol. I and II 1939/1953, Atomic Energy Commission, 1972, Appendices 1 and 7. Data is taken for years 1945-1953 for Soviet project. Source: Ed. By L.D. Ryabev, compiled by G.A. Goncharov , "USSR Atomic Project: Documents and Materials: 3 volumes",V. II. Atomic Bomb. 1945-1954. Book 5, Russian Federation, Ministry of Atomic Energy, RFNC-VNIIEF, 2000, pp.665-700.

[68] Ibid, pp.700-705.

[69] K. Kruglov, "Kak sozdavala's atomnaya promishlennost' SSSR [How the Soviet Atomic Industry Was Created]," Moscow, CNIIAtominform, 1995, pp.75-78.

[70] Ibid., pp.78-81.

Methods developed to restrain technology proliferation have decreased the ability of a state to acquire weapons-related technology

Technology proliferation trend indicates that three forms of technology acquisition have been used in the past: direct purchase, civilian nuclear cooperation and illicit nuclear marketing. The analysis indicates that the methods of technology acquisition evolved along with the measures that individual states and the international community at large implemented to restrain technology proliferation. Before the introduction of the Nuclear Non-Proliferation Treaty (NPT), states were not restricted by international norms to purchase technology from capable suppliers. After the NPT ratification, states used their “inalienable” right as stated in Articles 4 and 5 of the NPT not only to develop research, production and use of nuclear energy for peaceful purposes, but to receive civilian nuclear assistance to do this. When nuclear suppliers of the first tier organized the Nuclear Supplier Group and the London Suppliers Group as well as started to utilize export controls to monitor trade in sensitive technology, illicit ways of nuclear marketing became the primary route for weapons-related technology acquisition.[71]

The research conducted by M.D. Zentner, G.L. Coles, R.J. Talbert, however, indicates that it took states roughly equal amount of time to develop technology using indigenous development, foreign civilian assistance or illicit nuclear marketing routes. In some cases, for instance, uranium centrifuge technology, the minimum time to develop indigenous centrifuge technology was eight years, while the minimum time required to purchase, install and successfully operate foreign centrifuge technology for a non-nuclear weapons state was 11 years.[72] The author of this research finds this argument valid because Zentner, Coles and Talbert investigated technology proliferation programs from primary sources, included states

[71] M.D. Zentner, G.L. Coles, R.J. Talbert, “Nuclear Proliferation Technology Trend Analysis”, Pacific Northwest National Laboratory, 2005, p.33.
[72] Ibid, p.20 for Soviet case (8 years) and p.25 for Pakistan (11 years)

that have succeeded and failed to acquire technology and described the time period from 1945 to 2005.

Direct purchase before NPT allowed states to develop nuclear arsenals rather easy

Both the uranium enrichment and the plutonium production technology were available for purchase in the 1950's and 1960's before the introduction of the NPT. Five states that developed nuclear arsenals used direct purchase option for technology acquisition. The United States provided the plutonium production technology to Argentina and training to India. France assisted Israel in the Middle East and sold important technology to Pakistan. The Soviet Union provided the plutonium production technology and equipment to China and North Korea. Italy sold technology to Iraq. Yugoslavia developed a laboratory scale plutonium reprocessing facility from 1956 to 1966 by procuring technology and the PUREX method. Belgium built a laboratory-scale plutonium reprocessing facility in Pakistan between 1970 and 1973, having already developed the technology and equipment itself. [73]

It is important to note, however, that in those decades, the plutonium processing equipment could be purchased from the United States and Europe rather easily. At the same time, the uranium enrichment technology was not yet fully mastered and well-understood and therefore was not sold at the same scale.

Civilian nuclear cooperation after NPT limited states capability to acquire weapons-related technology

There is a general consensus in the literature with regards to how civilian nuclear cooperation allowed states mastering technology to produce fissile material after the introduction of the NPT in 1967. Matthew Fuhrmann establishes a direct connection between

[73] All of the above examples are drawn from the section on plutonium reprocessing acquisition trends described in M.D. Zentner, G.L. Coles, R.J. Talbert, "Nuclear Proliferation Technology Trend Analysis", Pacific Northwest National Laboratory, 2005, pp.91-97.

fissile material acquisition and civilian nuclear cooperation. His main argument is that because civilian assistance establishes an indigenous base of knowledge in nuclear technology, it could be useful for a nuclear weapons program for several reasons. First, the accumulated assistance reduces the costs of a nuclear weapons program, making states more capable of diverting into nuclear weapons programs when a crisis or security threat arises. Second, states that receive civilian aid are more likely to acquire nuclear weapons because important technological hurdles have been lowered, or in some cases, even removed.[74]

Contrary to conventional wisdom, however, known cases of transfer of both the plutonium production and the uranium enrichment technology through civilian nuclear cooperation have not occurred on the same scale as before the introduction of the NPT. Official cooperation in the uranium enrichment has been limited to the URENCO (the British, German, Netherlands Uranium Enrichment Company) gas centrifuge project and to the German-Brazilian agreement of 1976 involving the sale of eight reactors and a jet-nozzle isotope separation technology. Assistance to South Africa was provided by Germany in the development of its stationary-walled centrifuge.[75] On the plutonium production front, only nuclear power reactors and research reactors were sold under civilian nuclear cooperation agreement, while many deals involving transfer of plutonium reprocessing technology were cancelled. These include Germany to Egypt and Taiwan transfers in the mid-1970's, and United States to Argentina, and France to Pakistan transfers around the same period of time.[76]

[74] Matthew Fuhrmann, "Spreading Temptation: Proliferation and Peaceful Nuclear Cooperation Agreements," International Security, Vol. 34, No.1 (Summer, 2009), p.5.
[75] F. Barnaby, "How Nuclear Weapons Spread", Routledge, London, 1993, p.111-112.
[76] Data for Egypt and Taiwan cases is taken from Kurt M. Campbell, Robert J. Einhorn, and Mitchell B. Reiss, "Nuclear Tipping Point: Why states reconsider their nuclear choices", Brookings Institution Press, Washington, DC, 2004, pp.48-50 for Egypt case and pp.293-300 for Taiwan case. Data for Argentina and Pakistan cases is taken from F. Barnaby, "How Nuclear Weapons Spread", Routledge, London, 1993, pp.75-77 for Pakistan case and pp.100-102 for Argentina case.

Export controls moved nuclear weapons-related technology acquisition into illicit nuclear marketing domain

Three types of illicit nuclear marketing have been identified in the literature as ways developed to work around the norms of the international nonproliferation regime as well as the barriers raised by various groups of nuclear technology suppliers in the 1970's. First is procuring legal materials with the intent to further divert them into clandestine nuclear weapons programs. Second is government-to-government assistance in the development of nuclear fuel cycle capabilities in states that are not part of the NPT. Third is procuring nuclear materials from private nuclear networks. Matthew Kroenig and David Albright illustrate that each type of illicit nuclear marketing has accounted for reducing the technical barriers for achieving nuclear weapons capabilities and providing evidence that nuclear weapons activities of several countries have been advanced in such fashion.[77]

Again, contrary to the conventional wisdom, there are only five known cases of states who acquired or attempted to acquire technology using illicit nuclear markets. These countries are Iran, Iraq, Libya, North Korea (in case of uranium centrifuge technology), and Pakistan. Only Pakistan, however, managed to produce a nuclear arsenal using technology that it acquired through industrial espionage.[78] Pakistan is thought to be responsible for providing the means for Iran, Libya, and North Korea. [79] Pakistan is a classic example of a state that acquired technology using all three types of illicit nuclear marketing means. Buying components and assembling them in-country allowed Pakistan to develop an enrichment capability in nine years. After successfully bypassing existing international controls for its own program, Pakistan developed an illicit international procurement network. The key technology holders were located

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[77] Matthew Kroenig, "Importing the Bomb: Sensitive Nuclear Assistance and Nuclear Proliferation," Journal of Conflict Resolution, Vol. 53, No. 2 (April 2009), p.12.
[78] M.D. Zentner, G.L. Coles, R.J. Talbert, "Nuclear Proliferation Technology Trend Analysis", Pacific Northwest National Laboratory, 2005, p.33.
[79] Ibid, p.34.

in Pakistan, Europe, the United Arab Emirates, Turkey, South Africa, and Malaysia. The network also depended on a variety of manufacturing companies and suppliers on many continents.[80]

Military and industrial espionage as intervening variables for technology acquisition

The cases of Klaus Fuchs and A. Q. Khan are two known cases in which espionage contributed substantially to the development of nuclear weapons programs. In both cases, the material obtained through espionage substituted for experimentation and research.

In case of the Soviet atomic project, critical information was passed by British scientist Klaus Fuchs and other atomic spies who participated in the U.S. Manhattan project. Fuchs's first reports to Soviet authorities in 1943 were on the uranium isotope separation by means of gaseous diffusion. His second package of materials explaining the plutonium implosion bomb (including the detailed description of the internal layout of the U.S. plutonium nuclear weapon) was turned over to Soviet Union in February 1945. [81] The head of the Soviet atomic project, Igor Kurchatov, acknowledged later that Fuchs's material contributed as much as 50 percent of the technical knowledge needed to produce the first Soviet nuclear weapon and speeded up the nuclear weapon program by as much as a year or two.[82]

Technology availability as the second main barrier to producing fissile material

The analysis of nuclear weapons programs indicates that availability of technology is only one necessary condition for the successful acquisition of fissile material of scale required to produce a small arsenal of nuclear weapons. Technology had to be mastered to at least on the

[80] B. Larkin, “Designing Denuclearization”, Transaction Publishers, New Brunswick, 2008, pp.51-53.
[81] David Holloway, “The Soviet Union and the arms race”, Yale University Press, New Haven and London, 1983, p.23
[82] K. Kruglov, “Kak sozdavala's atomnaya promishlennost' SSSR [How the Soviet Atomic Industry Was Created],” Moscow, CNIIAtominform, 1995, p.47

level of pilot-scale production.[83] The analysis indicates that mastering the required technology generally follows a single pattern. First, laboratory-scale experiments are performed to understand the feasibility of developing corresponding technology for fissile material acquisition. Next, a state develops a pilot-scale facility to train the personnel and test the technology. Lastly, a state initiates a construction of an industrial-scale facility and produces the necessary equipment.

The analysis also indicates that states have experienced equal trouble progressing from laboratory-scale to pilot-scale facilities and from pilot-scale facilities to industrial-scale production. The following table illustrates how this worked for states in the past.

Table 3. Summary of different types of technology and time to pilot plant and industrial plant capacities

Technology	Number of countries with successful programs	Average time to pilot plant, years	Average time to industrial plant, years
Gaseous diffusion enrichment	5	5[84]	6
Centrifuge enrichment	7	8	14
Electromagnetic isotope separation	1	2	3
Aerodynamic isotope separation	1	7	18

[83] As illustrated by M.D. Zentner, G.L. Coles, R.J. Talbert a laboratory-scale facility produces milligrams of fissile material a year. In order to produce the required amount of fissile material to build a single nuclear weapons (6 to 25 kg), several hundreds of years are required. The pilot-scale facility, on the other hand, is built to produce at least the amount of fissile material for a single weapon a year. M.D. Zentner, G.L. Coles, R.J. Talbert, “Nuclear Proliferation Technology Trend Analysis”, Pacific Northwest National Laboratory, 2005, p.20.

[84] Richard Kokoski, “Technology and Proliferation of Nuclear Weapons”, SIPRI, Oxford University Press, 1995, pp. 23-25.

Graphite-moderated production reactors	6	1	2–11
Heavy-water moderated reactors	5	1	2–6
Research reactors	3	1	4–5
Reprocessing	13	6	10

Source: M.D. Zentner, G.L. Coles, R.J. Talbert, “Nuclear Proliferation Technology Trends”, Pacific Northwest National Laboratory, 2005, p.102

Zentner, Coles, and Talbert demonstrated that the time required for success in mastering technology varies widely and is strongly dependent on technology itself, help from nations who have already developed the technology or the nuclear and industrial maturity of the nation. Even when some of the research is proven feasible on the laboratory-scale, the consequent implementation is a difficult procedure. In case of the uranium enrichment, transition problems include the necessity to create cascades of machines completely sealed and capable of working non-stop in near-vacuum conditions. Corrosion-proof materials that can handle highly chemical active UF_6 have to be created. [85]

Zentner, Coles, and Talbert demonstrate the complexity of mastering technology correlated with time required to progress from one stage of technology development to another. The authors demonstrate that five countries have had indigenous uranium centrifuge development programs. The Soviet Union and the URENCO countries were the most successful. In case of Soviet Union mastering technology required, the creation of two national laboratories that included five large research universities and eight design bureaus with 2,100

[85] Complexity of uranium enrichment technology is summarized in different sections in M.D. Zentner, G.L. Coles, R.J. Talbert, “Nuclear Proliferation Technology Trend Analysis”, Pacific Northwest National Laboratory, 2005, p.12 for gaseous diffusion, p. 33 for gas centrifuge, p.41 for electromagnetic separation, p.55 for aerodynamic separation and p.59 for laser enrichment.

engineers employed. Time frames for initial development for the Soviet Union and the URENCO countries were relatively constant: 8–11 years for a demonstration facility, and 4–8 years later to have a production facility in operation.[86] The other three countries that attempted to develop technology (Brazil, India, and Japan) based their original programs on early URENCO designs and were less successful. It took India 17 years from a laboratory-scale facility to pilot-scale facility and 22 years for Brazil to do the same. These less successful programs spend much of their effort just trying to make their centrifuges operate successfully. [87] Brazil, for instance, only managed to get to pilot-scale production of low enriched fuel (20 percent enrichment) for its submarine propulsion program several years after the nuclear weapons program was officially renounced.[88]

Supply of natural uranium and financial constraints as alternative barriers for acquisition of fissile material

Several factors can be identified as influencing the speed of the nuclear weapons program development once the political decision to pursue such capabilities has been made. Among these the most prominent are two: financial contributions and natural uranium availability. The analysis of these factors concludes that even for small-scale projects, alternative solutions were developed by states to overcome these barriers.

Peter Pry estimated that Israel spent approximately $100 million on its nuclear weapons program from the start of Dimona reactor in 1963 to 1973 when Israel is believed to have acquired its first plutonium nuclear weapon.[89] It is a known fact that the defense budget of Israel from 1969 to 1973 constituted $1.6 billion annually, of which research and development

[86] Ibid, p.33.
[87] Ibid, p.31.
[88] Joseph Cirincione, Jon B. Wolfsthal, Miriam Rajkumar, “Deadly Arsenals: Nuclear, Biological and Chemical Threats,” Washington, D.C.: Carnegie Endowment for International Peace, 2005, p.397.
[89] Peter Pry, “Israel’s Nuclear Arsenal”, Westview Press, Colorado, pp.22-23.

amounted for approximately $70 million a year.[90] If $100 million are divided by the number of years spent to advance with the program (10), the cost per year of such program would constitute roughly 10 million dollars. Even if Pry's estimate is not correct, and assuming that Israel spent all of its research and development budget on a nuclear weapons program alone, the cost of such program could reach 700 million dollars. Comparing this number with an annual defense budget of Israel between 1969 and 1973 suggests that a nuclear weapon was an affordable option for Israel.[91] When required, states were able to secure financial resources for their nuclear programs to proceed.

Acquisition of natural uranium constituted a far greater problem than finding money for producing fissile material, but still not as nearly as important as mastering technology. Natural uranium production was clearly a problem for the Soviet atomic project. In 1945, the Soviet Union produced only 6.5 tons of uranium domestically, which represented 1/33th of the total amount of uranium required for the first Soviet production reactor.[92] The problem was resolved by capturing and transferring the uranium from Bulgaria, Czechoslovakia, and East Germany.[93] Israel solved its natural uranium supply problem for the Dimona reactor by hijacking British, French, and German uranium shipments as well as developing uranium production from Dead Sea minerals. According to *New York Times*, in 1968 a West German ship with 200 tons of the uranium ore "disappeared from the high seas and then reappeared several weeks later under a

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[90] T. Frieman, "Israel's Nuclear Option", Bulletin of the Atomic Scientists, Vol.30, 1974, p.33
[91] Data is taken from "The Military Balance" published by International Institute for Strategic Studies for relevant years.
[92] V. N. Novoselov, V.S. Tolstikov, *Taina "sorokovki" [Sorokovka Secret]*, Ekaterinburg, "Uralskii rabochii", 1995, p. 31.
[93] A.K. Kruglov, Kak sozdavala's atomnaya promishlennost' SSSR [How Soviet atomic industry was created], p.263

different flag, with a different name and different crew but without the uranium, which the U.S. investigators believed had been diverted to Israel."[94]

[94] H. Kohn and B. Newman, "Dayan Says Israelis Have the Capacity to Produce A-Bombs", New York Times, 25 June 1981.

Chapter 4. Concealing development of a fissile material acquisition program

Chapters 2 and 3 analyzed the routes for fissile material acquisition as well as main barriers that states face on their path to acquiring nuclear weapons capabilities. This purpose of this Chapter is to test **Hypothesis 3**. The uranium enrichment route is less detectable than the plutonium production route by modern intelligence collection means.

The analysis performed in this chapter concludes that the uranium enrichment route that utilizes gas centrifuge technology has a better chance of concealing its development than the plutonium reprocessing route. Such a conclusion is the result of analyzing different aspects of developing a clandestine fissile material acquisition program.

First, each type of a nuclear facility involved in the fissile material production route is assessed with respect to past record of detection. The results of the analysis indicate that nuclear facilities involved in the plutonium production route have been revealed more often in the past then nuclear facilities involved in the uranium enrichment route. In case of the uranium enrichment route, only gas centrifuge activities can be hidden relatively easily. Such facilities do not require substantial energy resources; they could be quite small and located in a building a size of a warehouse.

Second, both scale of a fissile material acquisition program and time for developing such program are analyzed in terms of probability of detection. The analysis indicates that developing a fissile material acquisition program of industrial-scale using both the uranium enrichment and the plutonium production routes significantly increases the probability of detection. At the same time, small-scale and distributed program does not allow producing enough fissile material to sustain even a small arsenal of nuclear weapons in a relatively short period of time (less than 5 years). The gas centrifuge enrichment technology is identified as the only process capable of concealing secrecy at a scale necessary to produce fissile material to manufacture a small arsenal of nuclear weapons.

Third, fissile material acquisition routes are analyzed with regards to how the origins of nuclear material, equipment, and facilities relate to the probability of detection. The analysis concludes that both the uranium enrichment and the plutonium reprocessing routes have equal hardships concealing secrecy both if nuclear programs are developed indigenously and in case when necessary material and technology is procured from foreign states.

Fourth, the effectiveness of using different techniques to conceal nuclear weapons program is analyzed. States employed camouflage, concealment, and deception to increase difficulties in locating and identifying facilities and equipment related to the production of materials for nuclear weapons. The analysis of effectiveness of such techniques illustrates that efforts to conceal the uranium enrichment facilities have been mixed, while attempts to conceal the plutonium reprocessing facilities have failed.

Finally, the diversion of nuclear fuel from a civilian nuclear program is analyzed as an alternative route for acquiring large amounts of nuclear material without detection. The analysis concludes that while it may seem as an attractive option because of its speed, it is highly unlikely that a state can use this route without prompt detection in the contemporary nonproliferation environment.

Plutonium production facilities have been discovered more often in the past than uranium enrichment facilities

Each type of a nuclear facility involved into a fissile material production route possesses a set of unique characteristics that make it less or more vulnerable for detection by intelligence means. The purpose of this section is to summarize these characteristics and illustrate how nuclear facilities involved into the plutonium production route and the uranium enrichment route have been detected in the past. The results of the analysis indicate that nuclear facilities involved in the plutonium production route have been revealed more often in the past then nuclear facilities involved in the uranium enrichment route. Furthermore, the probability of detecting nuclear facilities involved in the uranium enrichment route varies from low to high depending on the technology chosen to execute this route. The summary of findings is provided in Table 4.

Table 4. Probability of detection of each type of nuclear facility involved into fissile material production route by different intelligence collection disciplines

Intelligence collection discipline	The plutonium route		The uranium enrichment route
	Nuclear reactor	Reprocessing facility	Enrichment facility
Imaging and space intelligence (IMINT)	High	Low–High	Low–High
Signals intelligence (SIGINT)	High	Low–High	Low–-High
Measurements intelligence (MASINT)	High	Medium–High	Low–Medium
Human intelligence (HUMINT)	Low–High	Low–High	Low–High

Nuclear reactors have a strong record of detection

The probability of detection of a nuclear reactor by intelligence collection disciplines is very high. It can be rather easily detected using high-resolution space imagery sensors due to its size and distinct structures. Nuclear sites of the Soviet nuclear program were identified as early as the first U-2 flight over the territory of the Soviet Union in the late 1950's.[95] High temperatures inside a core of an operating reactor that reach several thousand degrees Celsius make a nuclear reactor especially vulnerable for detection using thermal imaging to locate associated warm spots on the ground's surface.[96] The activity of North Korean research reactor at Yongbyon has long been monitored by MASINT sensors employed by U.S. air reconnaissance and airborne collection system.[97]

High temperatures require large amounts of water to cool a reactor down. For this purposes the facility is usually built above the ground close to large reservoirs of water, which prompts its potential location.[98] Construction of underground facilities requires a large workforce and is highly visible to IMINT sensors. Soviet nuclear complex 815 was built underground in 1953 and included two production reactors, the plutonium reprocessing facility and weapons production factory. According to archival documents, 33, 000 workers were involved in the construction of the complex.[99]

After irradiation in a nuclear reactor, extracted fuel contains very high levels of radioactivity and is kept in a water reservoir at the same reactor facility for a period of several months. The radioactive gases released at this point have distinct tell-tales that could be easily

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[95] John Prados, "The Soviet estimate : U.S. intelligence analysis and Soviet strategic forces," Princeton, N.J.: Princeton University Press, 1982, p.32.
[96] National Academy of Sciences, ""Monitoring Nuclear Weapons and Nuclear Explosive Materials: An Assessment of Methods and Capabilities", Washington, DC, 2005, p.201.
[97] Richard Kokoski, "Technology and Proliferation of Nuclear Weapons", SIPRI, Oxford University Press, 1995, pp. 222-223.
[98] It is theoretically possible to construct a reactor underground, however, such construction has never been accomplished. See Charles W. Forsberg and Thomas Kress, "Underground reactor containments: An Option for the Future?", Paper N.159, American Nuclear Society, Florida, 2007.
[99] Ed. By L.D. Ryabev, compiled by G.A. Goncharov , "USSR Atomic Project: Documents and Materials: 3 volumes",V. II. Atomic Bomb. 1945-1954. Book 5, Russian Federation, Ministry of Atomic Energy, RFNC-VNIIEF, 2000, pp.635-640.

picked up by environmental samplings.[100] The United States has effectively used environmental samplings since 1948 to monitor the expansion of the Soviet nuclear infrastructure.[101]

Detection of plutonium reprocessing facilities largely depends on the size of the facility

The probability of detection of a plutonium reprocessing facility varies between low and high depending on the scale of the facility involved. The most reliable method for detecting a reprocessing facility is environmental sampling of the noble gas fission products that are released when spent fuel is reprocessed to obtain the plutonium.[102] Richard Kokoski estimated that even for a small-scale plutonium reprocessing facility producing around ten kilograms of plutonium a year, the krypton-85 "plume" can be detected at distances of around 15–20 km. This method is even more efficient when coupled with tracking heat signatures of the irradiated fuel with aerial reconnaissance using aircraft equipped with infrared radars.[103] The level of krypton-85, which is a signature gas both for reprocessing and reactor activities has long been monitored by the U.S. intelligence environmental sampling sensors.[104] Another method to determine the location of the reprocessing facility is laser detection and ranging system (LADAR), which can be tuned to analyze nitrous acid effluents resulting from the dissolution of the irradiated fuel in nitric acid.[105] There is no public record of how effective LADAR is in tracking the plutonium reprocessing facilities.

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[100] International Panel on Fissile Materials, "Global Fissile Material Report 2009", p.102, accessed through http://www.fissilematerials.org/ipfm/pages_us_en/documents/documents/documents.php.

[101] John Prados, "The Soviet estimate : U.S. intelligence analysis and Soviet strategic forces," Princeton, N.J.: Princeton University Press, 1982, pp.23-30.

[102] Richard Kokoski, "Technology and Proliferation of Nuclear Weapons", SIPRI, Oxford University Press, 1995, pp. 203-205.

[103] Ibid. pp. 205-211.

[104] Ibid, pp. 211-219.

[105]Ibid, pp. 219-220.

At the same time, Graham and Hansen assess that the probability of detecting a laboratory-scale reprocessing facility is rather small.[106] For instance, a North Korean plutonium reprocessing facility that separated only 100 grams of plutonium was revealed only by soil sampling during the ad hoc inspection conducted by the IAEA.[107]

Detection of an enrichment facility depends on the isotope separation technology used to enrich uranium

The probability of detection of an uranium enrichment facility varies significantly according to the type of enrichment technology used. As identified by Richard Kokoski "one of the hardest things on earth to hide is gaseous diffusion plant; its mere presence on the landscape, easily detected by satellites is a dead give-away of a nation's intentions".[108] David Albright estimated that any enrichment plant operating industrial-scale production of HEU has a reasonably high probability of detection by a "larger intelligence effort" that includes the analysis of human intelligence and communications intercepts along with imagery and measurements intelligence data.[109]

Both authors, however, acknowledge that hiding a small-scale uranium enrichment facility is easier than a small research reactor or a reprocessing facility. Unlike a nuclear reactor or a plutonium reprocessing facility, a uranium enrichment complex does not emit radioactive gases or produces large amounts of heat. For instance, a small-scale gas centrifuge plant needs only 200–300 isotope separation machines depending on the design to produce fissile material

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[106] T. Graham, K. A. Hansen, "Preventing catastrophe: The Use and Misuse of Intelligence in Efforts to Halt the Proliferation of Weapons of Mass Destruction", Stanford University Press, 2009, pp. 65-70.
[107] Ibid, pp. 160-163.
[108] Richard Kokoski, "Technology and Proliferation of Nuclear Weapons", SIPRI, Oxford University Press, 1995, p. 66.
[109] F. von Hippel, D. H. Albright, B.G. Levi, "Stopping the production of fissile material for weapons", Scientific American, vol.253, n.3, 1985, pp.32-33.

for a single nuclear weapons in a year. Such plants can be installed in a building the size of one or several warehouses.[110]

The uranium enrichment has the greatest probability of detection by SIGINT sensors because of its power usage.[111] Depending on the isotope separation technology used, the power requirement per enrichment work varies from several thousands to several dozens of thousands of KWh per SWU. A typical industrial-scale uranium enrichment plant consumes electricity enough to supply a city of a million households a year.[112] The only exception to this rule is the gas centrifuge technology; its KWh/SWU ratio ranges within 100–200 depending on the type of isotope separation machines used.[113]

The scale of fissile material acquisition programs has a positive correlation with the probability of detection

It is estimated that the scale of materials, equipment, staff and facilities involved into a nuclear weapons program has a positive correlation with the probability of detection of a fissile material acquisition program. [114] The higher the scale of the program, the higher is the probability to detect it.

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[110] The example uses SWU capacity for gas centrifuge machine of P-5 design. One isotope machines of this kind has capacity of 50 SWU/y. As estimated in Chapter 2, 4000 SWU is required to produce HEU for a single nuclear weapon. Therefore, 200 machines operating at full capacity is enough to produce HEU for a single nuclear weapons in a year. Dimensions for such machines is taken from Alexander Glazer's work "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation", Routledge, Taylor and Francis Group, Science and Global Security, 16:1-25, 2008, pp.8-11.

[111] Richard Kokoski, "Technology and Proliferation of Nuclear Weapons", SIPRI, Oxford University Press, 1995, p. 217-218.

[112] The estimation is done for gaseous diffusion technology. The capacity of such plant is around several million SWU/year and requires around 2500 KWh/SWU.

[113] For KWh/SWU comparison of different uranium enrichment technologies, see Table 5 on p.64 in Richard Kokoski, "Technology and Proliferation of Nuclear Weapons", SIPRI, Oxford University Press, 1995.

[114] A. K. Bollfrass, B.M. Blechman, "Elements of a Nuclear Disarmament Treaty", Henry L. Stimson Center. Washington, DC, 2010, p.229.

One simple example illustrates this clearly. A construction of a K-25 industrial-scale gaseous diffusion uranium enrichment plant for the U.S. atomic project required moving several millions cubic meters of earth, employing 15 to 20 thousand workers, and a construction of a 100-200 MWt power facility. Once constructed, such a facility occupied an area 800 meters long and 700 meters wide, operated several dozens of thousands of gaseous diffusion machines, and fed several millions of tons of UF_6 a day.[115] An industrial-scale reprocessing facility at Hanford was a smaller scale, nevertheless, quite easily detectable building. Once constructed it reached 300 meters in length, 40 meters in width and 40 meters in height and operated cranes of special construction to move the cases with highly-irradiated fuel into containers with nitric acid.[116]

At the same time, thinking small is not a panacea as correctly pointed out by Bruce Larkin. His analysis shows that the most attractive route for concealing a nuclear weapons program is to keep an extended network of pilot-scale facilities. Such facilities can be fit into a small factory building, employ up to a 1,000 people and require power as a standard metallurgic plant. This, however, does not decrease the probability of detection due to increased traffic of material and personnel between nuclear facilities.[117] Although Bruce Larkin provides no evidence to how that distributed program was effectively concealed in the past, his analysis looks valid. For instance, it requires almost 84 million kg of UF_6 to produce 1 kg of HEU.[118] UF_6 arrives at the uranium enrichment plant in a solid form as a cylinder that weights 14 tons.[119] This

[115] Richard G. Hewlett, Francis Ducan, "The New World: A History of the United States Atomic Energy Commission", Vol. I 1939/1946, Atomic Energy Commission, 1972, p.162.
[116] Richard G. Hewlett, Francis Ducan, "The New World: A History of the United States Atomic Energy Commission", Vol. I 1939/1946, Atomic Energy Commission, 1972, p.216
[117] B. Larkin, "Designing Denuclearization", Transaction Publishers, New Brunswick, 2008, pp.55-57.
[118] Richard Kokoski, "Technology and Proliferation of Nuclear Weapons", SIPRI, Oxford University Press, 1995, p. 23.
[119] Ibid, p.23.

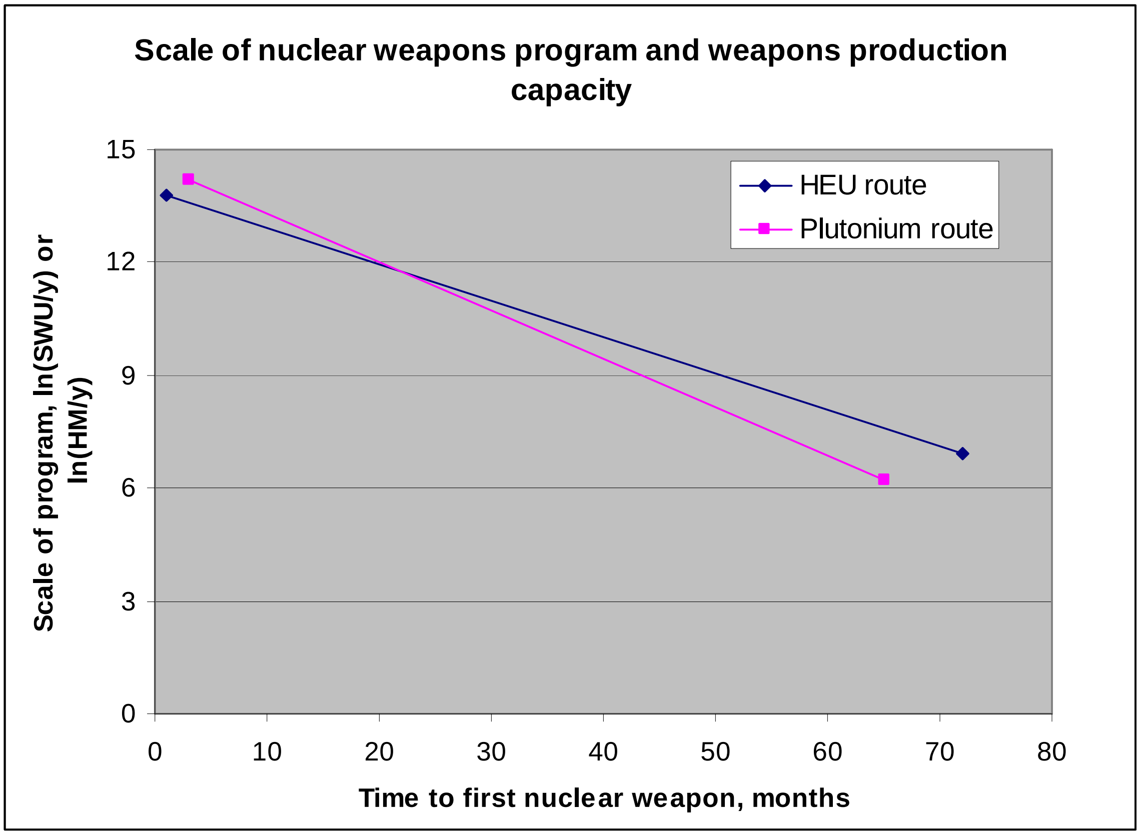
means that in order to produce HEU for a single nuclear weapon, 150 thousand cylinders of UF_6 must be transported between distributed small-scale facilities.

It is important to note that the smaller the scale of the program, the longer it takes to acquire the required amount of fissile material. Assuming that knowledge about the scale of the program suggests the capacity of a state to produce fissile material, the potential of keeping the program small undermines the credibility to use a nuclear weapon as a policy instrument. For instance, if a nuclear weapon is acquired as means of deterrence, a small arsenal can provoke a military attack instead of restraining it, a state's arsenal might not survive the initial attack, let alone have the capability to execute a retaliatory second-strike.[120]

A typical pilot-scale uranium enrichment or the plutonium reprocessing (including time for fuel irradiation in a nuclear reactor) program requires 5-6 years to produce fissile material for a single nuclear weapon. As the facility is extended and reaches the industrial-scale production, the time period reduced to months or even days per nuclear weapon. Figure 1 illustrates how this works. A pilot-scale facility enrichment facility of 1000 SWU/y capacity or a pilot-scale plutonium reprocessing facility of 1000 HM/y capacity can produce enough fissile material to build a single nuclear weapon in a time period of 65 to 75 months (5-6 years). When the capacity is extended and reaches industrial-scale production (millions of SWU/y for an uranium enrichment facility or millions of HM/y for a plutonium reprocessing facilities), the time frame for producing fissile material to manufacture a single nuclear weapons decreases to several days.

[120] Thomas Schelling in his book "Arms control" identified four factors that make deterrence work: capability, credibility, communication and rationality. Small-scale uranium enrichment or plutonium reprocessing program undermined both the capability and the credibility parameters for deterrence to work.

Figure 1. Scale of nuclear weapons program and weapons production capacity[121]



Uranium enrichment route allows shortening time frame to acquire fissile material by using nuclear fuel for nuclear power or research reactors

The starting point of the effort to produce a fissile material is a significant factor. If, for instance, a state utilizes a combination of uranium enrichment technologies and is able to produce or procure significant quantities of low enriched fuel (LEU) or even fuel for a research reactor, then a subsequent enrichment technology would only need to be about one-quarter the size that would be required if the starting point was natural uranium. When the size of the enrichment technology is assumed constant, the time to produce a nuclear weapon decreases significantly depending on the starting point of enrichment. Figure 2 illustrates how this works for

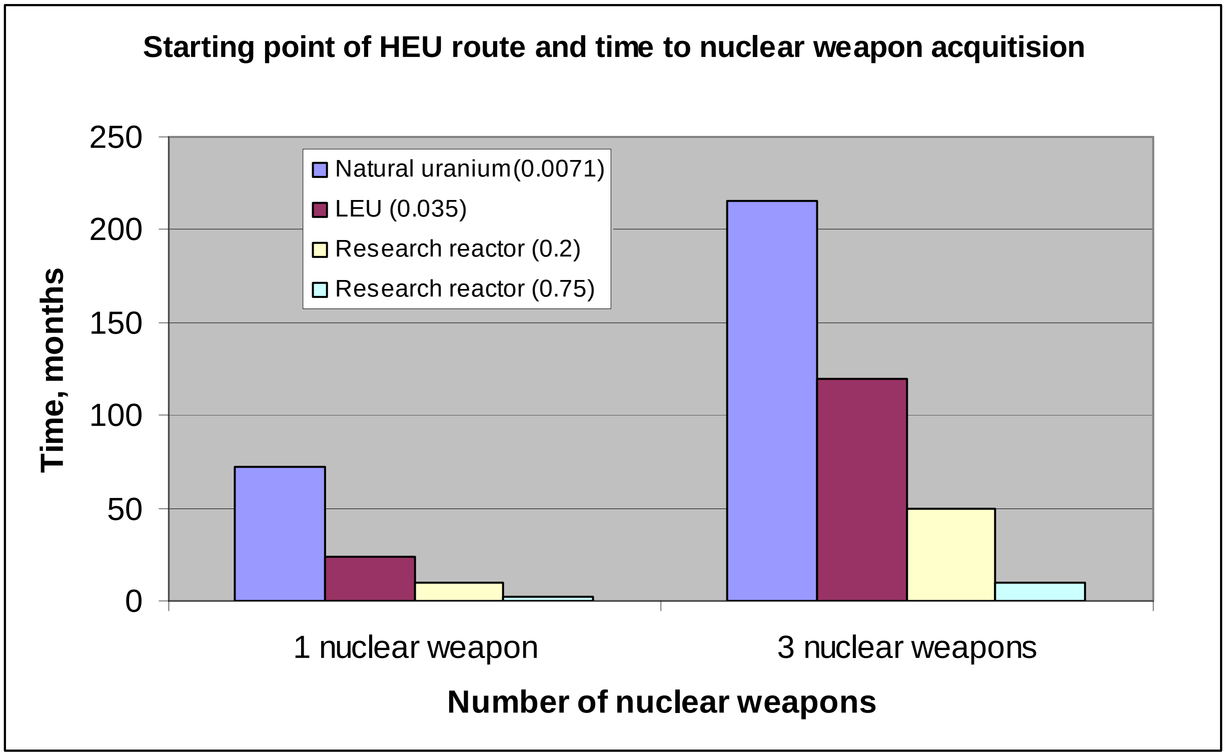
[121] Due to big difference between SWU/y or HM/y capacity of the pilot and industrial-scale facilities, the values along the Y axes are represented as LN(SWU/y) or LN(HM/y).

a typical pilot-scale enrichment facility. If a facility is supplied with natural uranium the timeframe for developing a single nuclear weapon is 65 months and 220 months for 3 nuclear weapons. In case when LEU fuel is fed into isotope separation machines, this timeframe reduces to 25 and 120 months correspondingly. If a research reactor fuel is used in an uranium enrichment facility, the timeframe for producing fissile material for a single nuclear weapon shortens to several months.

The same pattern can be observed if the industrial-scale facility is involved, but the time scale in this case is not months, but days. It is critically important to note that reconfiguration and reintroduction of feed of UF_6 or adjustment of such feed can be easily accomplished only at centrifuge enrichments plants. The cascades of isotope enrichment machines at the gaseous diffusion plant are organized in such a way that it takes weeks to months to reconfigure the feed at gaseous diffusion plants, but minutes at centrifuge plants.[122]

Figure 2. Time required to produce HEU for 1 and 3 nuclear weapons depending on the starting point

[122] Richard Kokoski, "Technology and Proliferation of Nuclear Weapons", SIPRI, Oxford University Press, 1995, p. 24.



The starting point factor is important for the uranium enrichment route only because the plutonium is extracted from irradiated fuel. While it may seem that acquiring enough LEU or even research reactor fuel on the market could significantly benefit the development of the nuclear weapons program through the uranium enrichment route, such activity will almost 100 percent lead to detection of any concealed nuclear facilities. As mentioned in Chapter 2, trade in natural uranium is not monitored by the IAEA, while trade in LEU and research reactor fuel is monitored and safeguarded by the international community. Therefore, trying to acquire any type of enriched fuel without having a nuclear reactor to feed it into will almost certainly arouse suspicion and point to state's intentions.[123]

[123] London Supplier Group guidelines, accessed online through http://cns.miis.edu/npr/pdfs/strula11.pdf.

Using foreign assistance to develop fissile material production program has a positive correlation with the probability of detection

For many clandestine processes, including both uranium enrichment and plutonium reprocessing activities, indigenous facilities have to be developed. Richard Kokoski estimated that the scope of such facilities depends on the ability of a state to procure necessary technology using civilian nuclear cooperation agreements as well as illicit nuclear networks. The more indigenous methods a state employs the greater is the chance of detection simply because more people are employed, more facilities are needed, and more infrastructure has to be created.[124] M.D. Zentner, G.L. Coles, R.J. Talbert estimated that indigenous development of uranium enrichment technology from laboratory-scale to pilot-scale production on average constitutes 8 years if indigenous research is involved and 9 years if technology is procured through illicit nuclear networks.[125] This suggests that procuring necessary materials, technology, and equipment from foreign suppliers increases both the time and the risk of detection because cross-border operations are involved. Critical equipment and components for the uranium enrichment and the plutonium production routes have long been listed on the export control lists; illicit transactions are likewise conducted under great scrutiny simply because of the limited range of suppliers in this category.[126]

Alexander K. Bollfrass estimated that if processes involve crossing borders and contracting with foreign nationals, additional risk is assumed to raise the odds of detection for every transaction.[127] Contracting foreign nationals for restricted expertise or procuring restricted

[124] Berhanykin Andemicael and John Mathiason, “Eliminating Weapons of Mass Destruction: Prospects for Effective International Verification”, Palgrave Macmillan, New York, 2005, pp.76-79.
[125] M.D. Zentner, G.L. Coles, R.J. Talbert, “Nuclear Proliferation Technology Trend Analysis”, Pacific Northwest National Laboratory, 2005, p.34.
[126] Record indicates that CIA has been aware of major illicit transfers of technology as well as the A.Q. Khan network. Berhanykin Andemicael and John Mathiason, “Eliminating Weapons of Mass Destruction: Prospects for Effective International Verification”, Palgrave Macmillan, New York, 2005, pp.84-87.
[127] A. K. Bollfrass, B.M. Blechman, “Elements of a Nuclear Disarmament Treaty”, Henry L. Stimson Center. Washington, DC, 2010, p.230.

technology from a foreign state can jeopardize the whole effort of keeping a secret nuclear weapons program. Procuring related but not-restricted technology can also arouse suspicion and result in unwanted intelligence attention.

Camouflage, concealment and deception as intervening variables

States have used camouflage, concealment, and deception to increase difficulties in locating and identifying facilities and equipment related to the production of materials for nuclear weapons. These techniques are not new; the Soviet Union started constructing "window-dressing" facilities as early as 1951.[128] The analysis indicates that efforts to conceal uranium enrichment facilities in the recent past have been mixed, while attempts to conceal nuclear reactors or plutonium reprocessing facilities have failed.

In case of uranium enrichment, the most recent record involves the Iranian, Iraqi, and South African facilities. The Iraqi centrifuge manufacture plant at Al Furat was discovered only after the Persian Gulf War despite the fact that the Iraqi calutron enrichment buildings were over 100 m long and required substantial energy resources. Iraq successfully utilized camouflage and deception techniques to hide its facilities. Among measures implemented were burying power lines underground, building light fences around the facilities and constantly moving equipment from one site to another.[129] In the case of South Africa, the Advens Laboratory, where the most work on the South African nuclear weapon was done, was not identified as a nuclear facility by the IAEA or the CIA until it was disclosed by the South African government in 1993. South Africa concealed this laboratory by installing the green roof of the building before either its internal walls were constructed or any recognizable equipment was delivered to the

[128] Ed. By L.D. Ryabev, compiled by G.A. Goncharov , "USSR Atomic Project: Documents and Materials: 3 volumes",V. II. Atomic Bomb. 1945-1954. Book 5, Russian Federation, Ministry of Atomic Energy, RFNC-VNIIEF, 2000, p.652.

[129] M. Hibbs, A. Maclachan, "No bomb-quantity HEU in Iraq, IAEA reports indicates", Nuclear Fuel, vol. 15, no.17, 1990, p.9

site.[130] At the same time, Iranian enrichment facilities were revealed twice: in 2002 by a HUMINT source and in 2009 by joint British-U.S. effort involving a range of intelligence agencies.[131]

Reprocessing facilities involved in chemical separation can be concealed by constructing a thick shielding for protection from the intense radioactivity and from distinctive emissions that can be detected over distance of several dozens of kilometers. The easiest way to do this is to build a clandestine facility next to the declared safeguarded reprocessing facility to help mask emissions. Evidence shows that this option has been tried but failed. Syria was developing a nuclear reactor and hiding a plutonium reprocessing facility under the reactor to cover emissions from reprocessing activities. In 2008, both facilities were destroyed by an Israeli air attack, while prior revealed by a joint U.S.-Israeli intelligence effort.[132] The North Korean research reactor and reprocessing facility at Yongbyon were revealed despite efforts to disguise the shutdown of the reactor and dismantling of the reprocessing facility prior to verification inspections.[133]

Diversion of fissile material from civilian nuclear programs as an alternative to clandestine acquisition is highly unlikely to be concealed

While diversion of fissile material from existing civilian nuclear program may appear as an attractive option for developing nuclear weapons capabilities, it is highly unlikely that a state can do so without prompt detection. Analysis indicates that the organization of safeguards and inspections in a contemporary nonproliferation environment leaves a state little chance of diverting even small quantities of fissile material without prompt detection.

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[130] J.R. Smith, "From dust to dust: history of S. Africa's bomb", Washington Post, 12 May 1993.
[131] Peter Crail, "Secret Iranian Enrichment Facility Revealed", Arms Control Association, October, 2009.
[132] T. Graham, K. Hansen, ""Preventing catastrophe: The Use and Misuse of Intelligence in Efforts to Halt the Proliferation of Weapons of Mass Destruction", Stanford University Press, 2009, p.182.
[133] Joseph Cirincione, Jon B. Wolfsthal, Miriam Rajkumar, "Deadly Arsenals: Nuclear, Biological and Chemical Threats," Washington, D.C.: Carnegie Endowment for International Peace, 2005, pp.279-284.

Contemporary nonproliferation regime largely depends on two verification systems – the Expanded Safeguards Agreement under the NPT and the International Monitoring System under the Comprehensive Test-Ban Treaty (CTBT).[134] Each verification system comprises a diverse set of technical mechanisms, ranging from sophisticated IMINT and MASINT capabilities to visual inspection by experts. Completeness and correctness are two concepts underlying these verification systems. Correctness of declared information is checked by inspections in order to provide assurances about the peaceful use of declared material and facilities.[135]

The quality of contemporary inspections leaves a state little space to maneuver with diversion of nuclear material without detection. The analysis performed by Francesco Calogero, Marvin L. Goldberg, and Sergei P. Kapitza indicates that the uranium conversion and fabrication facilities that handle LEU are inspected six times per year and those handling natural uranium are inspected four times per year. At one of these inspections in each case the annual Physical Inventory Verification (PIV) is conducted by the IAEA. At the PIV the presence of all items declared to be present in all material strata is confirmed. A statistically determined sample of the items in each stratum is inspected by weighting (in some cases by volume and density measurements), by using instruments, and by the withdrawal of samples for chemical analysis. The number of items measured and the measurements applied are such that there is a high probability that an abrupt or protracted (over the year) diversion of a significant quantity of nuclear material will be detected.[136]

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[134] Berhanykin Andemicael and John Mathiason, "Eliminating Weapons of Mass Destruction: Prospects for Effective International Verification", Palgrave Macmillan, New York, 2005, pp.61-62.
[135] Ibid, p. 63.
[136] Francesco Calogero, Marvin L. Goldberg, Sergei P. Kapitza, "Verification: Monitoring Disarmament", Westview Press, 1991, p.89

The other inspections during the year (5 for LEU handling facilities and 3 for natural uranium handling facilities) take place on a normal schedule throughout the year. One of the purposes of such inspections is to verify receipts and shipments of nuclear fuel as well as other inventory changes. Finished fuel pellets are sampled several times a year to quantify any differences between the operator's measurement system and the IAEA system to limit the effect of any such systematic difference on the IAEA ability to detect protracted diversion. Lastly, throughout the year, monthly reports of inventory and inventory changes are examined for consistency, and the inspection of the facility is recorded while reports are audited.[137]

[137] Ibid, pp. 80-87.

Chapter 5. Instruments to restrain or reverse fissile material acquisition programs

Chapters 2 and 3 analyzed the routes for fissile material acquisition as well as main barriers that states face on their path to acquiring nuclear weapons capabilities. Chapter 4 provided conclusions as to what fissile material acquisition route is better capable of concealing its development. The purpose of this Chapter is to test **Hypothesis 4**. Different external measures have been effective in reversing or restraining a state's uranium enrichment or plutonium reprocessing program when applied to different stages of program development.

All nuclear weapons programs have started in secrecy.[138] States tend to keep their nuclear programs clandestine for two reasons. First, states do not want other states to know of their nuclear weapons programs to protect the programs and their development. Second, states are concerned with protecting themselves from international or another nation's reaction that might follow the revelation of a nuclear weapons program.[139] For these purposes states have utilized various measures to conceal their nuclear intentions as long as they possible can. At some point, however, their nuclear intentions become known to the international community or at least to some national intelligence services.

The analysis performed in this chapter indicates that four types of external measures have been used by individual states or the international community at large as means to restrain or reverse nuclear weapons programs of other states. It concludes that diplomatic pressure has been generally effective in restraining the laboratory-scale effort of a state to produce fissile material. Sanctions have mostly failed to force a state to reverse nuclear weapons program when applied to any stage of the development of the fissile material acquisition program. Military

[138] All nuclear weapons programs were analyzed in this thesis and all of them started in secrecy.
[139] Scott D. Sagan, "Why Do States Build Nuclear Weapons?", International Security, Vol. 21, No.3, 1996-1997, p.2-3.

options have been successfully used to deny states a nuclear weapons programs at a laboratory and pilot-scale stages. Security assurances have also worked to restrain a state that acquired industrial scale capacity to produce fissile material from developing an arsenal of nuclear weapons.

Domestic factors are assessed in this chapter as alternative measures that influenced the decision to reverse or restrain fissile material acquisition programs in the past. The analysis indicates that a change in the leadership is a common factor that led to the reversal of fissile material acquisition programs.

Diplomatic pressure has worked successfully at the laboratory-scale stage of nuclear weapons program development

The analysis indicates that diplomatic pressure has worked successfully to restrain a state from acquiring fissile material in case two factors are present. First, a state that applies diplomatic pressure has the capability to force a government of a state desiring nuclear weapons to sign commitments not to engage in any weapons-related activities. Most prominent forms of such capability as identified by the analysis are security assurances and defense support. Second, diplomatic pressure is applied to the laboratory-scale stage of the development of the fissile material acquisition route. As Chapter 3 illustrated, the transition from laboratory-scale to pilot-scale facility takes on average 5–8 years. During that period of time, a state invests significant efforts in nuclear technology and nuclear infrastructure development as well as masters the required technology. If to the process from laboratory-scale to pilot-scale production of fissile material is successful, a state is much more reluctant to give it up.[140]

[140] For example, Brazilian centrifuge enrichment program still exists despite efforts to reverse nuclear weapons programs initiated by the civilian government in Brazil in the 1990's. Arturo Sotomayor Velázquez, "Civil-Military Affairs and Security Institutions in the Southern Cone: The Sources of Argentine-Brazilian Nuclear Cooperation," Latin American Politics and Society*,* Vol. 46, No. 4 (Winter, 2004), p.14.

Cases: South Korea, Taiwan, and Israel

The record of using diplomatic pressure can be illustrated by comparing South Korean and Taiwanese early pursuit for nuclear-related capabilities in contrast to Israel's nuclear program. Cases were selected on the following bases: all three states have long been U.S. allies, all three countries are located in highly volatile regional environment and the United States has had solid intelligence data revealing nuclear programs of these states at the very early laboratory-scale efforts.

According to Jonathan Pollack, South Korea established the Agency for Defense Development (ADD) and the Weapons Exploitation Committee in 1970. In late 1973, the ADD completed a long-term plan for development of nuclear weapons. When in 1975, CIA intelligence confirmed that Seoul had developed a program for nuclear weapons acquisition, the United States intervened with France and Canada to cut off any sales of sophisticated nuclear technology to South Korea. The United States pressured South Korea to sign the NPT, threatened to terminate all civilian nuclear energy cooperation and even end bilateral relations. The United States successfully used pressure in the form of defense support again in 1982 to reverse plutonium separation activities, and in 2000 to restrain the uranium enrichment efforts, both in laboratories and yielding minute quantities.[141]

Taiwan is a similar type of case. As Derek Mitchell explained, Taiwan began its nuclear weapons program shortly after China's 1964 nuclear test. In 1969 Taiwan procured a small heavy-water reactor from Canada. In 1972–1973, it tried to purchase technology for the plutonium reprocessing from France and Germany but failed. In 1976, the IAEA inspections accompanied by U.S. representatives to Taiwan resulted in the revelation of indigenous laboratory-scale plutonium reprocessing efforts. During late 1970's the United States repeatedly

[141] Kurt M. Campbell, Robert J. Einhorn, and Mitchell B. Reiss, "Nuclear Tipping Point: Why states reconsider their nuclear choices", Brookings Institution Press, Washington, DC, 2004, pp.254-270.

pressured Taiwan using defense and diplomatic support as leverage to force the state to close down the principal reactor and sign commitments not to acquire reprocessing facilities or engage in activities related to reprocessing. In 1988, when Taiwan once again turned to reprocessing, its intentions were revealed at the laboratory-scale stage by a longtime CIA agent. Following the pressure from the United States in the form of suspension of defense items shipments, the reprocessing facility was dismantled.[142]

Israel, on the other hand, represents a different kind of case. According to Peter Pry, Israel activated Dimona reactor and a laboratory-scale reprocessing facility at the Negev Nuclear Research Center in 1963. In 1964, the facilities were revealed by U.S. intelligence and Israel agreed to allow U.S. inspections of the facilities. During the following few years, the United States proposed to give Israel technical assistance and $40 million toward the construction of a nuclear desalination plant contingent upon Israel reversing its nuclear weapons ambitions. In 1967 Israel engaged into a six-day war with communist-backed Egypt. U.S. inspections and pressure slowly deteriorated starting with 1967 and were removed in 1969. While there is no direct evidence of this fact, one can suggest that the war changed the U.S. ability to apply pressure to Israel's in the changing strategic circumstances.[143]

Sanctions have generally failed to force states to reverse nuclear weapons programs at any stage of development

The analysis of use of sanctions indicates that sanctions failed to force states to reverse nuclear weapons programs both when applied to restrain the nuclear weapons activity and to penalize the country at large for other reasons. In fact, there is only one case of successful use of sanctions to reverse a state's nuclear weapons program, which is Libya. Even in this case,

[142] Ibid, p.293-300.
[143] P. Pry, "Israel's Nuclear Arsenal", Westview Press, Colorado, 1984, pp.15-17, 42-43.

sanctions were penalizing the country for other reasons and were not initially linked to nuclear weapons program.

Cases: South Africa, North Korea, Libya

According to Richard Kokoski, in 1977 a Soviet satellite obtained photographic evidence of South African test preparations in the Kalahari and alerted the United States. Even though diplomatic pressure immediately followed the discovery, and resulted in the South African commitment not to test a weapon, Pretoria had successfully launched the Y-plant of pilot scale (10.000 SWU/year) by 1978. This plant, however, was not revealed by intelligence services of any state and continued to operate under a mandatory arms embargo implemented by the UN Security Council against South Africa in 1977, followed by mandatory economic sanctions the same year and a mandatory embargo on oil and oil products in 1979.[144]

According to Frank Barnaby, North Korea has successfully built a pilot reprocessing plant during 1980–1990 and used nuclear fuel from its research reactor to extract weapons-grade plutonium. First efforts to pressure North Korea to reverse its nuclear program were made in 1994. Multilateral sanctions followed in 2006 after North Korea successfully tested a nuclear explosive device. In 2010, new sanctions were adopted that, contrary to expectations, have not restrained or reversed North Korea from continuing with the development of its nuclear program.[145]

According to Zentner and Talbert, Libya began to acquire the capability to perform gas centrifuge uranium enrichment in 1995. In 1997, the Libyan government received 20 assembled P1 centrifuges and components for 200 more centrifuges. Nine of these were assembled into a

[144] Richard Kokoski, “Technology and Proliferation of Nuclear Weapons”, SIPRI, Oxford University Press, 1995, pp.135-140.
[145] F. Barnaby, “How Nuclear Weapons Spread”, Routledge, London, 1993, pp.94-97

cascade in 2000. The first successful test was in October 2000, and three cascades had been assembled by April 2002.[146]

The analysis of use of sanctions against Libya indicates that the UN Security Council imposed sanctions on Libya in 1992 to press Tripoli to hand over two suspects wanted for the 1988 bombing of a U.S. Pan American Airways airliner over Lockerbie, Scotland. The council suspended (but did not lift) the sanctions against Libya in April 1999 after the Libyan government handed over the suspects for trial in a special court.[147]

In August 2003, Libya accepted responsibility for the bombing and agreed to a $2.7 billion settlement. In return, London and Washington immediately began to push the UN Security Council to lift all UN sanctions against Tripoli. As a permanent member with veto power, France agreed in principle to lift the sanctions, but urged a delay so that it could negotiate increased Libyan indemnity payments to its own citizens in connection with the 1989 bombing of a French UTA airliner over Niger. The council lifted sanctions in September 2003, and at the end of the year, Libya agreed to end efforts to produce nuclear weapons.[148]

Military options have a successful record of removing states capacity to continue with nuclear weapons program at both laboratory and pilot stages

Several conclusions can be reached by analyzing the record of using military options to restrain a state from pursuing nuclear weapons capabilities. First, a successful pointed military attack can only be executed at an unprotected facility. Second, a military attack can provoke a state to use every means possible to conceal its nuclear facilities as well as create "window-

[146] M.D. Zentner, G.L. Coles, R.J. Talbert, "Nuclear Proliferation Technology Trend Analysis", Pacific Northwest National Laboratory, 2005, p.28.
[147] The summary of sanction is taken from http://www.globalpolicy.org/component/content/category/195-libya.html.
[148] The summary of sanction is taken from http://www.globalpolicy.org/component/content/category/195-libya.html.

dressing" facilities to deceive another potential pointed military attack. Third, only a grand-scale military operation can completely remove nuclear weapons capabilities from a state.

Chances that a grand-scale military operation will be executed just to remove the nuclear weapons capabilities from a state are very small. Despite the fact that the United States used weapons of mass destruction as a pretext for the 2003 invasion of Iraq, the underlying idea behind this operation was to initiate a change in governance in the Middle East by democratizing Iraq and using it as an example for other nations in the region to follow.[149]

Cases: Iraq, Syria

According to Richard Kokoski, Iraq initiated its nuclear weapons program in 1972. In 1981 Israel has successfully bombed the Osiraq reactor. In the aftermath of this bombing, Saddam Hussein stated that the bombing taught Iraq that "they must shelter their vital projects from all attack." The real scale of the Iraqi program became fully known years after the 1991 Persian Gulf War. As a result of the military operation and the inspections that followed, the international community revealed that Iraq has utilized almost every conceivable means of obtaining fissile material, including both highly enriched uranium and weapons-grade plutonium. Furthermore, Iraq has successfully employed means of camouflage and deception to conceal its nuclear weapons program since 1981. At the time of invasion, Iraq has successfully completed the laboratory-scale experiments with EMIS enrichment and was constructing a pilot-scale EMIS enrichment facility. In the aftermath of the first Gulf War, Iraq's fissile material acquisition program was fully dismantled. It took the international community 8 years to reveal and dismantle the Iraqi nuclear infrastructure.[150]

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[149] Paul Pillar Talk, "Intelligence, Policy, and the War in Iraq," Council on Foreign Relations, March 7, 2006.
[150] Richard Kokoski, "Technology and Proliferation of Nuclear Weapons", SIPRI, Oxford University Press, 1995, pp.97-100

Thomas Graham and Keith Hansen indicate that Syria was constructing a small research reactor in the 2000’s. In 2008 the facility was revealed by a joint U.S.-Israel intelligence effort. The same year the facility was destroyed by an Israeli air attack. The IAEA confirmed in the aftermath of the attack, that traces of the uranium and special equipment were found at the site during inspections.[151]

Security assurance has been the only solid measure to prevent a development of a nuclear arsenal once a state has reached the industrial-scale production stage

Two conclusions can be reached by analyzing the use of security assurances as external instruments to restrain or reverse a state’s nuclear weapons program. First, security assurance is a prominent form of leverage when addressed to reverse the laboratory-scale efforts of producing fissile material using diplomatic pressure. Second, security assurances represent the only option that has kept states from acquiring a nuclear arsenal when they have developed industrial-scale capabilities to produce fissile material.

Cases: Japan, India

Japan began a national centrifuge enrichment development program in 1976. By 1984 Japan has successfully produced an industrial-scale plant (500.000 SWU/year), which by 1995 reached the capacity of 4 million SWU/year. Japan has also developed an industrial-scale reprocessing facility for commercial reactor fuel. Despite having the capability, Japan has refrained from developing an arsenal of nuclear weapons. This phenomenon is summarized by Kurt Campbell. He states that “although the credibility of the U.S. nuclear deterrence has never been tested in the case of Japan, it continues to lie at the heart of the security relationship between the United States and Japan. Indeed, the guarantee, and the U.S.-Japan security alliance in which it is embedded, provides the most important reason why Japan has not sought

[151] Graham, K. A. Hansen, “Preventing catastrophe: The Use and Misuse of Intelligence in Efforts to Halt the Proliferation of Weapons of Mass Destruction”, Stanford University Press, 2009, p.61-64, 162-163.

to develop an independent nuclear weapons capacity. Thanks to their continued faith in U.S. foreign and security policy, successive Japanese administration have refrained from fully developing the military potential commonly associated with a “normal” state.”[152]

India, on the other hand, is a case of a state seeking security assurances and developing nuclear weapons capabilities due to the failure to receive them. According to Frank Barnaby, in the early 1960’s, India began laboratory-scale reprocessing experiments in the plant at Trombay. The 1964 Chinese nuclear test forced India to seek security guarantees from the United States. Unable to get security assurance, India tried to influence the content of the NPT to embed legal protection for non-nuclear weapons states from a nuclear attack by a nuclear weapons state. Unable to receive such guarantees at the international level, India has not signed the NPT and turned to the Soviet Union for security assurance. By 1971, when such guarantees were obtained, India had already acquired enough fissile material for several nuclear weapons. Another war with Pakistan, in which India became embroiled later that year, bolstered India’s intention to use fissile material to build an arsenal of nuclear weapons.[153]

Domestic factors as alternative instruments for restraining or reversing states nuclear weapons programs

In some cases internal factors intervened and played a role in the decision of a state to restrain or reverse the fissile material acquisition program. The most prominent factor identified across the cases studied is change in the leadership of the corresponding state. Another important factor identified is the use of nuclear weapons programs as a means employed by one political group of a state to reduce power of another political group and consolidate control.

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[152] Kurt M. Campbell, Robert J. Einhorn, and Mitchell B. Reiss, “Nuclear Tipping Point: Why states reconsider their nuclear choices”, Brookings Institution Press, Washington, DC, 2004, pp.254-270.
[153] F. Barnaby, “How Nuclear Weapons Spread”, Routledge, London, 1993, pp. 68-72

Cases: Egypt, Brazil, and Argentina

According to Robert Einhorn in December 1960, the prime minister of Isreal, David Ben-Gurion, publicly revealed the construction of the Dimona reactor. A few days later Egyptian president, Gamal Abdel Nasser, announced that Egypt would have to acquire nuclear weapons at any price if Israel did so. During the early 1960's, the government of Egypt significantly increased the budget for nuclear program, recruited and trained nuclear specialists, and approached a number of countries for nuclear technology. In the mid-1960's, the cancellation of the nuclear deal with West Germany and the declining Egyptian economy significantly slowed down the development of the Egyptian nuclear program. In 1967, Egypt got embroiled into a Six-Day War and diverted attention away from nuclear weapons program. The death of Nasser in 1970 marked the end of Egypt's pursuit for nuclear weapons.[154]

As Joao Resende-Santos and Arturo Sotomayor Velázquez demonstrated the decision to denounce the nuclear weapons programs of Argentina and Brazil respectively was caused by the civil-military transitions (or shifts within the military leadership in case of Brazil in 1980) in these countries. The authors identify the main drivers that facilitated the October 1979 Tripartite Corpus-Itaipu Agreement and the May 1980 Accord on Cooperation for the Development and Application for the Peaceful Uses of Nuclear Energy (AMRE 1980a) as domestically driven security calculations by Argentina and the abertura or "political liberalization" policy by the Brazilian government.[155]

The evolution of civil-military relations and subsequent democratization of Argentina and Brazil contributed to institutionalizing of the nuclear security agreements between two countries in the 1990's. Three mechanisms allowed civilian leaders in both countries to perceive

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[154] Kurt M. Campbell, Robert J. Einhorn, and Mitchell B. Reiss, "Nuclear Tipping Point: Why states reconsider their nuclear choices", Brookings Institution Press, Washington, DC, 2004, pp.48-50.
[155] Joao Resende-Santos, "The Origins of Security Cooperation in the Southern Cone," Latin American Politics and Society, Vol. 44, No. 4 (Winter, 2002), pp.2-4.

institutions as means to control and subordinate the military and return the control of nuclear programs to the civilian authorities. These included omnibalancing, which is policy handling and managing uncertainty. Omnibalancing involved the policy of appeasing the external rival in order to reduce domestic sources of threat. Policy handling assumed the use of foreign policy tool to exclude certain organizations from the decisionmaking process. The management of uncertainty intended to formalize and institutionalize policymaking in the face of domestic uncertainty.[156]

[156] Arturo Sotomayor Velázquez, "Civil-Military Affairs and Security Institutions in the Southern Cone: The Sources of Argentine-Brazilian Nuclear Cooperation," Latin American Politics and Society, Vol. 46, No. 4 (Winter, 2004), p.2.

Chapter 6. Policy Implications and Recommendations

Policy Implications

This paper summarizes two implications for the contemporary nonproliferation environment.

Uranium enrichment approach is likely to be the proliferation route of choice in the contemporary nonproliferation environment

The analysis performed in Chapter 2 concluded that uranium enrichment requires less time, fewer steps, and is less expensive than using plutonium production to produce fissile material. The major obstacles, however, in pursuing either route for fissile material acquisition are technology availability and complexity. The analysis performed in Chapter 3 concluded that in the contemporary nonproliferation environment, both the uranium enrichment technology and the plutonium production technology are available and well-understood. The analysis performed in Chapter 4 concluded that the uranium enrichment route that utilizes gas centrifuge technology has a better chance of concealing its development than the plutonium reprocessing route. The overall analysis, therefore, implies that if a state were to choose between uranium enrichment and plutonium production for fissile material acquisition today, it will likely choose the uranium enrichment because the technology has the same availability, but the route itself is shorter, cheaper, and less detectable by modern intelligence collection means.

The main advantage of using plutonium technology remains simplicity and maturity. Production of heavy-water and research reactor technology has not changed for decades. Same can be said about the reprocessing technology. Most of it is based on 1955 PUREX and bismuth-phosphate methods, although small, laboratory research is ongoing in advanced reprocessing techniques. At the same time high visibility of the plutonium production route remains its main disadvantage. A chance that a state can hide a nuclear reactor is very small and without the reactor no plutonium can be produced.

The uranium enrichment technology, on the other hand, is evolving. Isotope separation methods continue to advance. Two enrichment technologies successfully used in weapons programs, electro-magnetic and aerodynamic isotope separation, are very expensive, difficult to operate, extremely power demanding but declassified and have a good record of concealing its development.[157] Gaseous diffusion enrichment facilities are in most cases old and scheduled for closure.[158] Gas centrifuge technology appears to be the modern trend in the uranium enrichment. Several generations of gas centrifuges have already been developed, and have increased machine capacity by more than 50 times.[159] And still new designs are being researched. At the current level of development of a gas centrifuge technology a state only needs 100–200 isotope separation machines of last design to produce enough fissile material for a single nuclear weapon in a year.[160] Such a cascade has very good chances of concealing its development because it can be installed in a simple warehouse and does not require significant power resources.[161]

States are likely to continue to exploit loopholes in the current verification system to develop clandestine nuclear facilities

The analysis performed in Chapter 4 concluded that the organization of safeguards and inspections in a contemporary nonproliferation environment leaves a state little chance of diverting even small quantities of fissile material without detection. At the same time the

[157] M.D. Zentner, G.L. Coles, R.J. Talbert, "Nuclear Proliferation Technology Trend Analysis", Pacific Northwest National Laboratory, 2005, p.102.
[158] Ibid, p.103.
[159] Alexander Glazer, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation", Routledge, Taylor and Francis Group, Science and Global Security, 16:1-25, 2008, pp.8-11.
[160] P-5 centrifuge capacity is 50 SWU/y. Ibid., p.9.
[161] Richard Kokoski, "Technology and Proliferation of Nuclear Weapons," SIPRI, Oxford University Press, 1995, p. 23.

safeguards are only applied to declared facilities and therefore their effect is limited to detecting and deterring violations at known sites. Monitoring and revealing clandestine activities requires integration of national intelligence means with international expertise and control. This is yet a work in progress and states desiring nuclear weapons capabilities can exploit the loopholes of the existing system to their advantage.

As indicated in Chapter 4, correctness and completeness are two concepts underlying the contemporary verification system. Correctness of declared information is checked by inspections and provides effective assurances about the peaceful use of declared material and facilities form. Completeness, at the same time, is a crucial step in revealing clandestine activities. It often depends on additional information states are asked to provide supplemented by information assembled from other sources, often from intelligence agencies. The combination of two levels is expected to provide a reasonable assurance regarding the absence of undeclared material, facilities, and illicit activities.[162]

However, the completeness level is by no means as solid as safeguards. There exist no programs within international verification organizations that directly monitor trade flows in the nuclear materials, equipment, and facilities. Instead, both the IAEA and the CTBT depend on a series of informal agreements among suppliers that could provide the required information. Moreover, none of the arrangements involves a systematic collection or publication of information. The information is exchanged, but not analyzed centrally, and it is up to individual states to use the information. Without information about denial of export permits to potentially

[162] B. Andemicael, J. Mathiason, "Eliminating Weapons of Mass Destruction: Prospects for Effective International Verification", Palgrave Macmillan, New York, 2005, pp.76-82.

sensitive technology, there is no credible method for verifying that certain technology was not supplied or even requested.[163]

Policy Recommendations

According to the IAEA, over 40 states are seriously considering nuclear power as a sustainable source of energy. The global nuclear marketplace is more active today than it has been in at last 20 years. Countries in Latin America, Southeast Asia, the Middle East, and Africa have expressed a desire to begin or revive civilian nuclear programs. Many of these countries are already requested and receiving assistance from capable suppliers. The promotion of nuclear power must be addressed properly to ensure the renaissance of nuclear power, not nuclear proliferation.

First policy recommendation: Involve the IAEA at the early stages of planning nuclear infrastructure

As indicated by the analysis in Chapter 4, successful and early detection of future clandestine weapons efforts will be significantly easier if there were greater transparency about the nuclear programs of all states, including their inventories of plutonium and highly enriched uranium and the capability of a state to make such materials. One of the initiatives that the IAEA has been undertaking since 2004 in this context is providing consultations to states who wish to pursue nuclear power with regards to legal procedures, energy planning, site selection, supplier choice, and safeguards implementation. Involvement of the international organization responsible for assuring use of nuclear power for peaceful purposes at an early stage allows not only establishing early history of state's nuclear activities, but educating a state of its rights and obligations under the current nonproliferation environment. At the same time, involving IAEA at the early stages of the development of the nuclear infrastructure will allow establishing early

[163] Ibid, pp. 76-82.

databases for nuclear-related activities of a state and therefore improve intelligence with regards to both activities and trends. At the moment, however, the IAEA is only conducting workshops and seminars for states requesting agency assistance in developing their nuclear infrastructure.[164]

Second policy recommendation: Incorporate intelligence support into the current verification regime

As indicates by the analysis in Chapter 4, the safeguards regime implemented by the IAEA serves as a strong deterrent for states to acquire fissile material through diversion. However, changes in the current verification regime are required to deal with the possibility of detecting undeclared facilities. First, high-quality intelligence information, particularly high-resolution IMINT and SIGINT that might reveal the construction and operation of clandestine nuclear facilities must be incorporated in the current verification process. At the moment, such information is available only through national intelligence services and can be provided upon request. By having intelligence information, the IAEA can act accordingly with ad hoc inspections to prevent a state from pursuing clandestine activities on very short notice. Second, the IAEA must receive funding to implement extensive environmental monitoring in addition to inspections. This ability would substantially improve the ability to detect undeclared facilities by detecting the distinctive radioactive or chemical substances emitted during their operation.

Third policy recommendation: Expand the scope for on-site inspections

As indicated by the analysis in Chapter 2, trade in natural uranium is not monitored or regulated by the IAEA at the moment. The author suggests that the chance of detecting clandestine nuclear facilities could be increased by expanding the scope of safeguards to include the uranium mining and milling operations. Currently safeguards begin when the

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[164] Information about workshops and seminars is taken from the IAEA website: http://www-pub.iaea.org/MTCD/Meetings/Meetings2007.asp.

uranium is converted into a chemical form suitable for fuel fabrication or the uranium enrichment; inventories of refined natural uranium are neither reported nor safeguarded. Moreover, the IAEA's authority to inspect undeclared sites on short notice must be improved dramatically. Current safeguards agreements include provisions for "special inspections" at undeclared sites, but these inspections must be carried out in consultation with the state. In practice, the IAEA must notify the state in advance, provide reasonable justification for the inspection, and obtain a state permission. Such practice must be implemented as are ad hoc inspections for declared facilities. The IAEA in this case will have both the capability and the authority to reveal clandestine activities if suspicions arise.

Fourth policy recommendation: Establish international uranium enrichment centers

As indicated by the analysis in Chapter 3 states have developed alternative ways to acquire weapons-related technology. The author suggests that for nuclear energy to play its full role in the future there is a need to increase the level of assurance that non-nuclear weapon states will not use the most sensitive nuclear technology toward developing nuclear weapons-related capabilities. Such assurance can be provided by establishing an international system for production and use of nuclear materials based on experience and authority of the IAEA. This move from autonomous national nuclear activity to international development of nuclear energy for peaceful purposes will serve several purposes. Most important it will provide an elevated level of assurance that nuclear reactors and material are used exclusively for peaceful purposes. In terms of nuclear fuel production the idea of establishing international and regional nuclear fuel centers must be advanced. States jointly owning a nuclear enrichment center will have higher incentives to jointly control nuclear-related activities of their neighbors. Regional and international fission material storage centers for managing sensitive and irradiated nuclear fuel must be implemented to make sure that proliferation will not be performed at the back-end of the nuclear cycle.

Iranian Nuclear Program

Standing aside from the general implications and recommendations for the nuclear non-proliferation regime at large is the issue of Iran's nuclear program. The issue is addressed in this thesis for two reasons. First, Iran has been developing its uranium enrichment program for over 20 years now and has reached pilot-scale production capacity.[165] Second, The international community, led by the United States, has tried several strategies in deterring Iran from producing fissile material for a nuclear weapon in the past. Most recent actions include revealing the secret uranium enrichment facility and organizing permanent members of the UN Security Council to sanction Iran in case Iran does not transfer the LEU it possesses to a third state for further enrichment. Such a policy has a clear purpose of delaying the Iranian nuclear program from becoming operational in a sense of being able to establish operational industrial-scale uranium enrichment production by placing the secret facility under the IAEA safeguards and deny Iran the possession of the stockpile of LEU it has produced. Despite efforts applied, Iran has been progressively advancing its uranium enrichment program.

Policy Implication: Sanctions will not likely restrain Iran from developing industrial-scale capacity for fissile material acquisition

In November 2009, the IAEA conducted a physical inventory verification at Fuel Enrichment Plant (FEP) at Natanz and verified that in February 2010, Iran moved approximately 1950 kg of low enriched UF6 (3.47 percent U235) from FEP at Natanz to the pilot FEP feed

165 M.D. Zentner, G.L. Coles, R.J. Talbert, "Nuclear Proliferation Technology Trend Analysis", Pacific Northwest National Laboratory, 2005, p.33.

station and provided the IAEA with mass spectrometry results which indicate that enrichment levels of up to 19.8 percent U-235 were obtained at that facility.[166]

The data provided by the IAEA has two major implications. First, Iran has already acquired enough LEU to produce fissile material for two nuclear weapons of first implosion design.[167] Second, Iran has successfully tested the first cascades of its isotope separation machines capable of producing weapons-usable material on the industrial level. Based on the analysis performed in Chapter 3, Iran's timeline for producing a nuclear weapon varies from 5 to 7 years depending on two factors: how fast Iran can progress technically and how determined Iran is to acquire nuclear weapons capabilities.

The same analysis also indicates that the likelihood of a state reversing its fissile material acquisition program at this stage of the development is not very high. Evidence supports that conclusion. The revelation of clandestine uranium enrichment facility in 2009 provides all reasons to believe that Iran has been steadily obtaining technology expertise through legal civilian nuclear cooperation and developing a parallel clandestine military program.

Cases of reversal studied in Chapter 5 provide several policy implications for contemporary U.S. strategy toward Iran. First implication indicates that sanctions have not worked successfully to reverse or restrain the nuclear weapons program when the state passes the pilot-scale stage of development of its fissile material acquisition program. Second, diplomatic pressure applied by the United States toward Iran is also likely to fail because the United States lacks the necessary leverage to implement its pressure. Security assurance has

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[166] IAEA, "Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council Resolutions 1737 (2006), 1747 (2007), 1803 (2008) and 1835 (2008) in the Islamic Republic of Iran",18 February, 2010"

[167] 678kg of 3.47 percent UF6 is required to produce 25 kg of 93 percent weapons-usable UF6.

been identified as the only solid measure to restrain a fissile material acquisition program of a state with similar uranium enrichment production capacity as Iran currently has.

First policy recommendation: Involve Iran in regional and transnational issues to eliminate its security concerns

Based on policy implications this thesis suggests that the optimal strategy for the United States and the international community at large to restrain Iran from acquiring fissile material programs is to provide the time necessary for Iran's proliferation motivations to change as well as simultaneously address state's security threats and provide Iran with alternative avenues through which to acquire international prestige.

The United States must start with reconsidering its current stance on Iran's enrichment program. By accepting the peaceful application of the program and cutting down harsh rhetoric against Iran's technical capabilities, the United States can help reduce Iran's sense of insecurity. Holding the larger negotiation process hostage to technology denial efforts inhibits attempts to address Iran's proliferation motivations.

As a next step, the United States must start implementing efforts to eliminate Iran's security proliferation driver. Gradually reengaging Iran in transnational issues, both in Iraq and Afghanistan, can effectively change Iran's perception of regional security landscape. The cooperation has proved to work in the past: in 2001, the United States and Iran cooperated to set up a government in Afghanistan. Such reengagement not only targets Iran's security concerns but it also provides Iran with alternative route to increase its international prestige. The military capabilities for such mechanism exist, although diplomatic capabilities have yet to be created.

Second policy recommendation: Deny Iran of critical technology within the legal context of the global non-proliferation regime

The technology denial must, however, continue within legal context of global nonproliferation regime to reveal any clandestine activity. The verification and monitoring capabilities the United States has already developed through that regime represent a significant lever to deny Iran technical capabilities to progress with its nuclear program. Intelligence-sharing with allies is a way to improve such capabilities. Monitoring trade flows in enrichment technology, a field where the United States relies mostly on gentlemen agreements between suppliers, is another way of extending U.S. technology denial capabilities.

Appendix A

Table 5. Approximate minimum critical mass for weapons use

Type of material	As Metal
Weapons-grade plutonium	8
Highly-enriched uranium (93% U-235) for a nuclear weapon of implosion design	25
Highly-enriched uranium (93% U-235) for a nuclear weapon of gun-type design	60
Plutonium extracted from commercial reactors	8
Research reactor fuel (20% enriched U-235)	75

Source: IAEA Safeguards Glossary, IAEA/SG/INF/1. p.21

Table 6. Uranium resources

Country	Reasonable assured resources	
	Reserves, tons	%
Australia	1,243,000	23
Kazakhstan	817,000	15
Russia	546,000	10
South Africa	435,000	8
Canada	423,000	8
USA	342,000	6
Brazil	278,000	5
Namibia	275,000	5
Niger	274,000	5
Ukraine	200,000	4
Jordan	112,000	2
Other	520,000	9

Source: OECD Nuclear Energy Agency and IAEA, "Uranium: Resource, Production and Demand", 2007 p.18-19

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