Journal of Strategic Trade Control
Vol. 3, February 2025

Development of uranium and plutonium based nuclear weapons—what impacts the choice of fissile material route?

Sophie Grape,[*1] *Erik Branger,*[*2] *Vitaly Fedchenko,*[*3] *Cecilia Gustavsson,*[*4] *Robert E. Kelley*[*5]

Abstract

This paper examines the underlying reasons why states have chosen to pursue a particular fissile material route in their nuclear weapons development. This analysis is conducted using case studies that describe historical developments and events, alongside an evaluation of their impact on the choice of fissile material route. Key areas of interest include the role of uranium resources, the visibility or covert nature of nuclear weapons activities, international relations, military delivery systems, and measures imposed by the export controls and nuclear safeguards regimes. The results of the work show that although uranium resources play a role, they impact the route in only one case. Insight into whether or not the nuclear weapon program is conducted openly or covertly does not seem to have impacted the selected fissile material route much, and the same can be said about the military delivery systems. In contrast, international relations, both in terms of government-to-government relations and proliferation networks, appear as far more important. The impact of export control and safeguards measures is shown to depend heavily on the context of international relations and the unique circumstances of each case.

Keywords
Fissile material route, uranium, plutonium, case study, motivation, nuclear weapons.

[*1] S. Grape is a Associate Professor of Applied Nuclear Physics at Uppsala University, working on nuclear safeguards, non-proliferation and disarmament. She is also co-founder of the Alva Myrdal Centre for Nuclear Disarmament at Uppsala University.
[*2] E. Branger is a researcher at Uppsala University, working on nuclear safeguards, non-proliferation and disarmament. His main work is on non-destructive assay of spent nuclear fuel for safeguards purposes, using gamma, neutron and Cherenkov light measurements.
[*3] V. Fedchenko is a Senior Researcher in SIPRI's Weapons of Mass Destruction Programme, responsible for nuclear security issues and the political, technological and educational dimensions of nuclear arms control and non-proliferation. He is the author or co-author of multiple publications on nuclear forensics, nuclear security, and nuclear non-proliferation.
[*4] C. Gustavsson is an Associate Professor in Applied Nuclear Physics at Uppsala University with a background in experimental nuclear physics. She is currently a member of the Working Group on Technical Verification and Monitoring at the Alva Myrdal Centre for Nuclear Disarmament.
[*5] R. E. Kelley is a nuclear engineer with a background in reactor operations, enrichment technology, plutonium R&D and intelligence analysis. He has served as a Group Leader at the Lawrence Livermore National Laboratory and Los Alamos, as Director of the USDOE Remote Sensing Laboratory, and as a Director of the IAEA specializing in cases of illicit weapons programs.

Article info

Submission date: September 12, 2024. Acceptance date: January 16, 2025. Publication date: February 10, 2025.

How to cite

S. Grape, E. Branger, V. Fedchenko, C. Gustavsson, R.E. Kelley, "Development of uranium and plutonium based nuclear weapons—what impacts the choice of fissile material route?," *Journal of Strategic Trade Control,* Vol. 3, (February 2025).
DOI: 10.25518/2952-7597.148

Publisher

European Studies Unit (ESU), University of Liège

Peer review

This article has been peer-reviewed through the journal's standard double-anonymous peer review, where both the reviewers and authors are anonymized during review.

1. Introduction

Nuclear weapons (NWs) are not easy to develop. The most challenging part is the production of fissile material, including the transformation of the material into a suitable form.[1] Nonetheless, many countries have decided to pursue NWs, some overtly and others clandestinely. States that possess NWs have shown that the acquisition of nuclear weapons under a nuclear weapons program (NWP) is a major endeavor that requires dedication, time, funding and competence. To deter states from developing NWs, multilateral export control regimes control technologies and equipment of a sensitive nature. Most significant are export controls on means to clandestinely produce fissile material; these focus heavily on enrichment and reprocessing technologies.[2] In addition, international nuclear safeguards are in place in signatory states to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and in non-signatories that have concluded safeguards agreements with the International Atomic Energy Agency (IAEA) to prevent the misuse of civilian facilities and materials, ensuring the early detection of any unauthorized activities.

States pursuing NWs must set priorities regarding the direction and scope of activities, with one important priority being whether the state aims to develop weapons based on uranium, plutonium, or both. NWs contain a core of fissile material, used to sustain the fission chain reaction. This material consists of either weapon-grade uranium enriched to around 90% of U-235, or plutonium with a very high Pu-239 content, known as weapons-grade plutonium.[3] The first nuclear weapon state (NWS) to develop and test NWs, the United States, developed both types of NW in parallel. A few states followed this lead, while others decided early on to develop only one type of NW, or to switch routes as new opportunities opened.

[1] Sico van der Meer, "States' Motivations to Acquire or Forgo Nuclear Weapons: Four Factors of Influence," *Journal of Military & Strategic Studies,* Vol. 17, n.1 (2016), pp. 209–236.
[2] Stephen Herzog, "The Nuclear Fuel Cycle and the Proliferation 'Danger Zone," *Journal for Peace and Nuclear Disarmament,* Vol. 3, n. 1 (2020), pp. 60–86; International Atomic Energy Agency, *"Communication received from the Permanent Mission of Kazakhstan to the International Atomic Energy Agency regarding Certain Member States' Guidelines for the Export of Nuclear Material, Equipment and Technology"*, INFCIRC/254/Rev.14/Part 1, October 18, 2019.
[3] It should be noted that it is not impossible to sustain a fission chain reaction with other materials. As the level of Pu-239 decreases and the amount of Pu-240 increases, the difficulty of producing a reliable weapon decreases, as the risk for pre-initiation increases. However, it is generally accepted that reliable nuclear weapons can be built with high-burn-up plutonium using increasingly sophisticated designs.

The motivations for states to develop NWs have been extensively studied in the social sciences,[4] with technical publications outlining the possible pathways to acquisition. For example, the IAEA's "Physical Model" describes technologies and processes for acquiring weapons-usable material and weaponization,[5] while other models map the nuclear fuel cycle for uranium and plutonium-based weapons.[6] However, fewer studies analyze why specific routes are chosen, such as a 1994 study that briefly examined the motivations of 13 states pursuing uranium and/or plutonium routes.[7]

In this article, we go beyond that work, by conducting a new, independent analysis 30 years after the initial analysis. In addition, we will attempt to draw conclusions that can guide competent non-proliferation authorities and safeguards experts to look for signs indicating efforts to manufacture NWs. It is important to understand the reasons why a country has chosen a specific route, as this can help focus efforts on preventing additional states from pursuing the same route. However, this requires knowing what to look for, and flag events as relevant to follow-up. These signs could include nuclear facilities, processes or activities to manufacture NW, but also e.g., other infrastructures, explicit policies, research efforts and human resources, including technical assistance as well as knowledge transfers.

This paper examines a number of states that have pursued NWs, analyzing information on historical developments to gain a better understanding of why the states chose to pursue a specific route in the *early* stages of their initial NW developments. The goal is to assist with resource allocations and developments in the non-proliferation community to prevent further NW proliferation and to provide recommendations that may promote nuclear disarmament. The case studies demonstrate the uniqueness of NW developments in each state,

---

[4] See, for example: Scott D. Sagan, "Why Do States Build Nuclear Weapons? Three Models in Search of a Bomb," *International Security,* Vol. 21, no. 3 (Winter 1996-1997), pp. 54-86; Marlene Da Cruz, "Why Do States Acquire Nuclear Weapons? A Theoretical Framework in Assessing Nuclear Proliferation in Israel, Iran and Saudi Arabia," *Political Analysis,* Vol. 21, article 2 (2020); van der Meer, "States' Motivations to Acquire or Forgo Nuclear Weapons".

[5] Zunqi Liu and Samir Morsy, "Development of the physical model", Symposium on International Safeguards: Verification and Nuclear Material Security, Vienna, Austria, October 29 – November 2 (2001) IAEA-SM-367/13/07.

[6] United States Department of Defense, *Nuclear Matters Handbook (Revised)*, 2020, pp. 191-208, <https://www.acq.osd.mil/ncbdp/nm/NMHB2020rev/docs/NMHB2020rev.pdf>.

[7] Joel Ullom, "Enriched uranium versus plutonium: Proliferant preferences in the choice of fissile material", *Nonproliferation Review,* Vol. 2, no. 1 (1994), pp. 1-15.

analyzing the specific approach employed by the state from several different perspectives.

Section 2 briefly explains the signatures of a NW development program and section 3 introduces the ten different cases studied in this work. Section 4 is the analysis section, and includes sections on e.g. resource availability, international relations and control regimes. Section 5 is a conclusion and outlook section.

2. Signatures of a nuclear weapon development program

Uranium enrichment facilities are central to the uranium route, while the plutonium route requires reactors and reprocessing facilities. Uranium enrichment facilities are easier to conceal than nuclear reactors as enrichment facilities can be made more compact and with fewer detectable emissions.[8] Potential signatures of enrichment activities could include items from industrial suppliers such as vacuum components and special corrosion-resistant materials. These industries are part of the supply chain for the NW program, and such trade usually leaves a procurement trail detectable by intelligence, or export control regimes. The most relevant export control regime is the Nuclear Suppliers Group (NSG), a group of potential nuclear supplier countries that strive to control nuclear proliferation in accordance with the NPT by developing and following technical guidelines for proliferation-related exports.[9] Two NSG guidelines are published by the IAEA as INFCIRC/254 Part 1 and Part 2, containing information on materials, components and technologies either specifically made for nuclear use (Trigger List), or so-called "dual-use" materials, components and technologies.

The plutonium route requires reactors that are more difficult to conceal. Satellite imaging tools can be used to potentially identify, e.g., reactor buildings, their cooling towers, or heat discharge plumes. The plutonium route also requires reprocessing. In the military fuel cycle, plutonium is typically recovered from low-burnup fuel. Different states have shown interest in reprocessing spent nuclear fuel, most notably the five NWSs and the four additional states possessing NWs. In addition, a few states

[8] International Panel on Fissile Materials, *Global Fissile Material Report 2010; Balancing the books: Production and Stocks*, Fifth annual report, December 17, 2010, <https://fissilematerials.org/publications/2010/12/global_fissile_material_report_4.html>.

[9] Nuclear Suppliers Group Official Website, n.d.,< https://www.nuclearsuppliersgroup.org/index.php/en/>.

with only civilian nuclear energy have also operated reprocessing facilities.[10]

2.1 Production of fissile material

Uranium is required to feed both uranium-based and plutonium-based NWs. It occurs naturally in low concentrations in uranium ore. Uranium-based NWs require an increase in the abundance of one uranium isotope in a process known as uranium enrichment. The preferred processes were electromagnetic separation and gaseous diffusion in the 1940's, and later gas centrifuges. Uranium enrichment equipment and know-how for NW production can be developed locally or acquired illegally, e.g. through proliferation networks and espionage, due to export control restrictions.

Plutonium weapons require uranium fuel in plutonium-producing reactors. Many reactors used to produce plutonium for NWs originated from the civilian Atoms for Peace initiative.[11] They were low-power heavy-water reactors (often under IAEA safeguards) operated on natural or low-enriched uranium (LEU), although small light-water moderated research reactors running on highly enriched uranium (HEU) were also provided by the US and Soviet Union. The reactors were built with turn-key technology, as donor states wanted to discourage receiving states from developing enrichment and reprocessing. The low enrichment level required frequent refueling, sometimes while the reactor was running (on-line refueling). This feature can be misused to produce plutonium from low-burnup fuel, which is much more attractive for use in NWs than plutonium from high-burnup fuel.

2.2 Delivery system constraints

This paper is limited to first generation weapons of simple one-stage systems. The delivery means of NWs may generate constraints, largely about the potential weight and diameter of the weapon. Single-stage early plutonium-based weapons are typically geometrically smaller and lighter than uranium weapons, among other due to the smaller critical mass of

[10] International Panel on Fissile Materials, "Global Fissile Material Report 2022 Fifty Years of the Nuclear Non-Proliferation Treaty: Nuclear Weapons, Fissile Materials, and Nuclear Energy" (2022), p. 23. <https://fissilematerials.org/library/gfmr22.pdf>; David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996 World Inventories, Capabilities and Policies*, SIPRI Publications, Oxford university press, 1997, pp. 148-192.

[11] Fuhrmann, Matthew, *Atomic Assistance: How "Atoms for Peace" Programs Cause Nuclear Insecurity*, (United States: Cornell University Press: 2012), pp. 180-206.

plutonium compared to uranium. The US Department of Energy stated in an unclassified document that a nuclear explosive device (NED) can be made with 4 kg of plutonium.[12] The document does not state the corresponding mass for HEU, but unclassified and unverified NGO estimates are about 12 kg.[13] A plutonium core surrounded by high explosives is much lighter than a uranium device, with the difference in diameter being much smaller than the mass advantage (e.g. a simple 4 kg plutonium sphere has a diameter of about 7.4 cm, while a 12 kg uranium sphere has a diameter of about 10.6 cm). If NED designers are constrained by weight, they will pursue the plutonium path for the weight and size advantages. The high-explosive diameter and mass is roughly comparable to the compressed fissile mass, meaning that we might expect the high explosive to be about three times as heavy for a uranium core as a plutonium one.

The perceived adversaries will also affect the choice of delivery system. If the main adversary is a neighboring state, there are fewer range constraints and any NW would suffice. If the adversary has limited defensive capability, basic aircraft or crude missiles may be sufficient. If a state perceives a distant strategic adversary, weight becomes a major concern and plutonium the preferred route.

2.3 Additional considerations—naval propulsion programs

All known naval propulsion systems require enriched uranium. Historically, this was HEU enriched to 50%-97%, although enrichments down to 20% or even 5% are possible in vessels with other constraints such as frequent refueling cycles. If a state is determined to build naval nuclear propulsion, especially nuclear submarines, it is likely that the state also develops uranium enrichment capabilities to secure the supply chain. It is unlikely that any state will provide enriched uranium to other states developing military propulsion, except within very tight alliances like the trilateral security pact AUKUS. This means that each state must develop its own enrichment capability. Plans for naval propulsion may provide an engineering incentive to develop uranium enrichment capability, which in turn could make HEU for NW an option. For example, India has produced

---

12 U.S. Department of Energy, Office of Declassification, "*Restricted data declassification decisions 1946 to the present*", U.S. Department of Energy, Office of Declassification (RDD7), (January 1, 2001), <https://sgp.fas.org/othergov/doe/rdd-7.html#I23>.

13 Alexander Glaser, "On the Proliferation Potential of Uranium Fuel for Research Reactors at Various Enrichment Levels." *Science & Global Security,* Vol.14, no. 1 (2006), pp. 3–4.

plutonium for NEDs, but the country's determined interest in nuclear submarines is developing a need for domestic enrichment.

3. Case studies

In this work, we have selected ten states and categorized them into one of the following four categories:

- States that have pursued both the uranium and plutonium routes simultaneously,
- States that have pursued only the uranium route,
- States that have pursued only the plutonium route, and
- States that have refocused their efforts on a route other than the one originally explored.

Although there is some overlap between the first and fourth categories, the fourth category is intended to describe states that abandon one route in favor of another one, rather than exploring both simultaneously, examples being states switching directions following AQ Khan's uranium enrichment efforts. We focus on the early stages of nuclear weapons development, the point at which states lack most or all infrastructure necessary for a nuclear weapons program. This is because we are interested in the initial steps taken by the state, before the first nuclear weapons were fully developed, and what considerations impacted the initial choice of fissile material route.

3.1 States that have pursued both routes

3.1.1 United States

The United States was the first nuclear weapons state. During World War II, many brilliant physicists, metallurgists, chemists, and engineers contributed to the development of the first NWs in the Manhattan Project. Under the Manhattan Project, the US committed huge resources to undertake a massive project with no precedent and no guarantee of success. Early on it explored both fissile material routes, because there were no precedents or experiences available for either one. Funds were allocated to construct several uranium enrichment plants and a nuclear reactor for plutonium production.[14] It is estimated that about half of the

[14] Richard G. Hewlett, and Oscar E. Anderson, Jr, *History of the United States Atomic Energy Commission. Volume I. 1939 / 1946, The New World*, (The Philadelphia State University Press: 1962), <https://www.energy.gov/management/articles/hewlett-and-anderson-new-world>.

overall project cost of the Manhattan project went to the construction and operation of uranium enrichment facilities. Including the costs and labor for plutonium production and separation, as well as uranium enrichment, that cost increased to about 80%.[15] Different options for uranium enrichment were considered and both electromagnetic and gaseous diffusion methods were pursued. One facility was constructed for each industrial scale technology in Oak Ridge, Tennessee. On the plutonium route, the first research reactor, Chicago Pile 1, went critical in 1942, and plans were made for larger graphite-moderated reactors at the Hanford site, close to a plutonium separation facility.[16] Several graphite reactor prototypes were constructed. Four reprocessing facilities employing chemical separation of elements were also constructed. The separated plutonium was shipped to Los Alamos where two different NW designs were being developed: the uranium gun-type design and the plutonium implosion design.[17] In addition to these nuclear infrastructures and resources, the Manhattan Project also required large amounts of other types of resources such as human capital and electricity. With respect to delivery systems, the US depended solely on aircraft-delivered nuclear weapons until well after 1959 before trying to fit nuclear warheads on missiles. [18]

3.1.2 Soviet Union/Russia

The Soviet Union was largely aware of the secret NWP in the US through espionage. The first Soviet research institution working on NWs production (Laboratory No. 2, later LIPAN) was created in February 1943. Initially, it focused on designing graphite-moderated reactors for the production of plutonium, seemingly motivated by the example of Fermi's 1942 experiment achieving the first controlled chain reaction.[19] However, as soon as World War II was over, the Soviet Union also dedicated resources to research on uranium enrichment methods. Small initial efforts to separate uranium isotopes can be traced back to 1944.[20] The

---

[15] Alex Wellerstein, "Manhattan project", Encyclopedia of the History of Science (2019), <https://ethos.lps.library.cmu.edu/article/id/22/>.

[16] "*The selection of Hanford WA (1942-1943),*" US Department of Energy, The Manhattan Project—an interactive history, < https://www.osti.gov/opennet/manhattan-project-history/Places/Hanford/hanford-selection.html#:~:text=On%20December%2031%2C%20Matthias%20and,and%20gave%20it%20his%20approval>.

[17] Richard Rhodes, *The making of the atomic bomb*, (United Kingdom: Simon & Schuster, 1995), pp. 577-79, 701-702.

[18] David Kindy, "The Indelible Enola Gay", *Smithsonian Magazine*, July 30, 2020.

[19] Arkadii Kruglov, *The History of the Soviet Atomic Industry*, 1st edition, CRC Press, 2002, pp. 36-44.

[20] Kruglov, *The History of the Soviet Atomic Industry*, p. 129.

first Soviet nuclear explosion in 1949 used plutonium from graphite-moderated reactors. The first Soviet HEU nuclear test was conducted at the Semipalatinsk test site on October 18, 1951, utilizing enriched uranium produced at the gaseous diffusion plant in 1949-50. By 1951, the Soviet Union's production of HEU for weapons was approximately 1 kg per day.[21] This clearly indicates that the Soviet Union pursued both plutonium and HEU routes in parallel. The Soviets continued to produce plutonium in graphite-moderated reactors for many decades. The Soviet Union produced much larger warheads than the US in the early stages, thus when land-based missile programs were considered in the 1950's, Soviet missile designers were forced to build large missiles with significant carrying capacity.

3.2 States that have pursued only the uranium route

3.2.1 South Africa

Nuclear activities started in 1957, when South Africa signed a 50-year collaboration project with the US under Atoms for Peace, which allowed the acquisition of a HEU-fueled reactor. South Africa has significant uranium reserves, and in the early 1970's it was decided to mine and sell uranium ore concentrate. Uranium would have higher sales value if it were enriched, and an indigenous aerodynamic enrichment process for uranium enrichment was developed.[22] It required a huge capital industrial infrastructure, a dangerous hydrogen carrier gas and was not very efficient. With growing enrichment capability, the purpose of enrichment changed to production for NWs.[23] In 1971, a program to explore peaceful nuclear explosions was approved. It is not completely clear when this program turned military, but IAEA safeguards officials estimate that this happened around 1974.[24] South Africa has operated commercial nuclear power plants using imported LEU fuel since 1984. These were never part of the NWP.

South Africa briefly traded materials such as uranium and tritium with Israel (the beneficiary being largely Israel), as both countries were largely

[21] Kruglov, *The History of the Soviet Atomic Industry*, p. 147.
[22] "Uranium Production, History and Usage of Uranium", Uranium Enrichment and Gas Centrifuge Technology, Federation of American Scientists, 2013, <https://programs.fas.org/ssp/nukes/fuelcycle/centrifuges/U_production.html>.
[23] Robert E. Kelley, *A Technical Retrospective of the Former South African Nuclear Weapon Programme*, SIPRI (2020), p. 4, pp.136-142.
[24] Roy E. Horton, "Out of (South) Africa Pretoria's nuclear weapons experience," INSS Occasional paper 27, *Counterproliferation series*, USAF Institute for national security studies, USAF Academy, Colorado (1999), pp. 5-6.

disconnected from trade agreements in general. South Africa assisted Israel with logistical arrangements to conduct an atmospheric nuclear test in the South Atlantic, but there was no exchange of nuclear weapons design information.[25] South Africa acquired centrifuge information from Urenco, but did not exploit it in its weapons program. At the time of the development of NWs, South Africa was involved in the South African Border War (1966-1990). Regarding delivery systems, South Africa planned to use aircraft, but also considered missile-based delivery systems.[26] The South African program succeeded in building crude weapons but failed to deliver them in time to assist in the Angolan war. The program was dissolved due to this failure and the significant governmental changes following the end of the apartheid regime.

3.3 States that have pursued only the plutonium route

3.3.1 Sweden

Sweden has a history of neutrality policy, including a strong national defense and the idea of self-sufficiency in military technologies. Sweden initiated NW research in 1945 through the Swedish Defense Research Agency (FOA), and later the company AB Atomenergi was founded and tasked with the objective of promoting civilian nuclear energy. AB Atomenergi and FOA jointly planned for the infrastructure required to produce plutonium for Swedish NWs.[27]

Early NW research focused on material acquisition, especially on uranium from Swedish mines. Heavy water was to be imported from Norway. Facilities for uranium mining, extraction and research were built, including a uranium fuel research laboratory and a uranium extraction facility.[28] Several reactors were constructed: a heavy-water moderated research reactor fueled with (French) natural uranium, a light-water moderated research reactor, and commercial heavy-water reactor producing heat and

[25] Sasha Polakow-Suransky, *The Unspoken Alliance: Israel's Secret Relationship with Apartheid South Africa*, (USA: Pantheon Books, 2010), p.7; Chris McGreal, "Revealed: how Israel offered to sell South Africa nuclear weapons", *The Guardian,* May 24, 2010.
[26] Horton, "Out of (South) Africa Pretoria's nuclear weapons experience", p. 9.
[27] Thomas Jonter, "The Swedish Plans to Acquire Nuclear Weapons, 1945–1968: An Analysis of the Technical Preparations", *Science & Global Security,* Vol. 18, no. 2 (2010), pp. 61-86.
[28] Niko Marsic, and Bertil Grundfelt, "Kartläggning av äldre anläggningar där radioaktivt material har lagrats eller hanterats," Swedish Radiation Safety Authority, Report 2013:23, ISSN 2000-0456.

electricity. Land was also acquired for building a reprocessing facility.[29] Uranium enrichment was never seriously considered, as the uranium path was considered too technically demanding and expensive.[30] For delivering the tactical NWs, Sweden had in mind domestically produced aircraft, although also land-attack missiles and submarine torpedoes were in the pipe-line for development during the 50s and 60s.[31] All Swedish plans for a NW were abandoned with the signing of the NPT in 1968.

3.3.2 Israel

Having Israel has consistently remained ambiguous regarding its NWP with very limited information available.[32] Thus, there is considerable uncertainty about the number and type of NWs.[33] The center of Israel's nuclear material production is the Dimona site, featuring a heavy-water moderated reactor for plutonium production, a fuel fabrication plant, and a plutonium separation plant. Facilities at the Dimona site were provided by France in the 1950’s and early 1960’s.[34] The facility has been supplied with both imported and domestically mined uranium.[35] The power of the reactor was later increased, possibly up to 150 MWth, and it is also likely used for tritium production.[36] Israel supplied South Africa with about 30 g of tritium around 1985, showing that they had sufficient production to allow exports.[37]

---

[29] Thomas Jonter, “Försvarets forskningsanstalt och planerna på svenska kärnvapen,” SKI Rapport, SKI-R-01-5 (2001).

[30] Jonter, “Försvarets forskningsanstalt och planerna på svenska kärnvapen”, p. 24.

[31] Jonter, “Försvarets forskningsanstalt och planerna på svenska kärnvapen”, p.50.

[32] International Panel on Fissile Materials*, Global Fissile Material Report 2010*, pp. 107-116; David Albright, “Israel’s Military Plutonium Inventory”, Institute for Science and International Security (2015).

[33] Alexander Glaser, Julien de Troullioud de Lanversin, “Plutonium and Tritium Production in Israel’s Dimona Reactor, 1964–2020”, *Science & Global Security,* Vol. 29, no. 2 (2021); Shannon N. Kile and Hans M. Kristensen, “IX. Israeli nuclear forces”, in *SIPRI Yearbook 2023, Armaments, Disarmament and International Security*, SIPRI Publishing, Oxford University Press (2024); Hans Kristensen, Matt Korda, M. “Nuclear Notebook: Israeli nuclear weapons, 2022”, *Bulletin of the Atomic Scientists*, January 17 (2022).

[34] Albright, “Israel’s Military Plutonium Inventory”; Wisconsin Project on Nuclear Arms Control, “Israel’s Plutonium Production,” July 1, 1996, <https://www.wisconsinproject.org/israel-plutonium-production/>.

[35] Wisconsin Project on Nuclear Arms Control, “Israel’s Uranium Processing and Enrichment,” July 1, 1996, <https://www.wisconsinproject.org/israel-uranium-processing-and-enrichment/>.

[36] David Albright, “Israel’s Military Plutonium Inventory”.

[37] International Panel on Fissile Materials*, Global Fissile Material Report 2010*, p. 115.

There appears to be an Israeli interest in uranium enrichment technology, though it is unknown if alleged facilities are on an industrial or a research scale.[38] It does appear as if significant enrichment activities started no earlier than the 1980's.[39] There are also allegations that Israel obtained very high-enriched uranium (VHEU) from the US during the 1960's.[40] At that point, Israel was well on the way to develop plutonium-based NWs.[41]

3.3.3 India

India embraced nuclear energy in the 1950s, influenced by Homi Bhabha's concern about India's future energy needs. Debates began about whether or not India should also acquire NWs.[42] Bhabha's vision centered on a fuel cycle with uranium reactors, producing plutonium in thorium breeders.[43] This cycle could rely on the use of heavy-water reactors, avoiding uranium enrichment. India obtained the CIRUS heavy-water research reactor from Canada in 1954. While CIRUS was under construction, India was designing and building a pilot fuel reprocessing facility named Phoenix. The Phoenix plant, combined with CIRUS, provided India with its first weapons-grade plutonium in 1964.[44] The plutonium separated from the CIRUS fuel was labeled "peaceful" to comply with Canadian requirements. Around 1964, India initiated theoretical work on nuclear explosions.[45] Ten years later, the first nuclear test explosion, a "peaceful nuclear explosion," was conducted. Weaponization of NEDs did not occur until the late 1980s.[46]

---

[38] Albright, "Israel's Military Plutonium Inventory".
[39] International Panel on Fissile Materials, *Global Fissile Material Report 2010*, p. 115.
[40] The 1965 NUMEC affair is an alleged theft of 100 kilograms of weapon-grade uranium for proliferation purposes. See Gilinsky, V. and Mattson, R. J., "Did Israel steal bomb-grade uranium from the United States?," *Bulletin of the Atomic Scientists*, April 17, 2014; and Gilinsky, V. and Mattson, R. J., "Revisiting the NUMEC affair", *Bulletin of the Atomic Scientists*, vol. 66, no. 2 (2010).
[41] Albright, "Israel's Military Plutonium Inventory".
[42] George Perkovich, *India's Nuclear Bomb: the Impact On Global Proliferation*, (Berkeley: University of California Press, 1999), pp. 14-59.
[43] Robert E. Kelley, "Supply Dilemmas", *Jane's Intelligence Review*, (July 2020), pp. 44-49. For description of Homi Bhabha long-term vision for Indian nuclear program see: Perkovich, *India's Nuclear Bomb*, p. 26.
[44] Perkovich, *India's Nuclear Bomb*, pp. 28, 543.
[45] Perkovich, *India's Nuclear Bomb*, p. 82.
[46] "India Nuclear Overview", Factsheet, Nuclear Threat Initiative, November 4, 2019, <https://www.nti.org/analysis/articles/india-nuclear/>.

India also built a gas centrifuge enrichment plant near Mysore.[47] The plant was commissioned in 1990, suggesting that the uranium path was not pursued in India's earliest NWP. India also has a firm commitment to nuclear-powered submarines, which would require significant uranium enrichment capabilities.[48] India considered aircraft and short-range missiles for the NW delivery early on.[49]

3.4 States that have refocused their efforts on another route than originally explored

3.4.1 Pakistan

As an early member of the IAEA, Pakistan benefited greatly from international assistance in establishing civilian nuclear power, especially from the US in the late 1950s.[50] Pakistan also acquired a pressurized heavy water reactor from Canada. The reactor, Karachi-1 or KANUPP was placed under IAEA safeguards.[51] A driving force behind the contract with Canada was India's acquisition of the CIRUS reactor a few years earlier. The 1974 test explosion by India, led Canada to cancel the cooperation with Pakistan on the KANUPP reactor, unless Pakistan accepted full safeguards. Pakistan had an obsolete "Type 66" safeguards agreement in which it could choose which facilities and items it would declare and reserve the right to exclude others.[52] Pakistan did not accept full safeguards, nor did it sign the NPT. Instead, it chose to expand its nuclear

---

[47] "Current Issues: Operating Uranium Conversion/Enrichment and Nuclear Fuel Plants – Asia," WISE Uranium Project, accessed September 15, 2024, <https://www.wise-uranium.org/eopasi.html>.

[48] "Countries: India", International Panel on Fissile Materials, April 13, 2024, <https://fissilematerials.org/countries/india.html>.

[49] Christopher Clary, "Twenty-Five Years of Overt Nuclear India", *Arms Control Association,* October 2023.

[50] Zia Mian, "Fevered with Dreams of the Future: The Coming of the Atomic Age to Pakistan", in Itty Abraham, ed., *South Asian Cultures of the Bomb*, (Bloomington: Indiana University Press, 2009), pp. 20-40.

[51] International Atomic Energy Agency, "The Text of The Safeguards Transfer Agreement Relating To The Bilateral Agreement Between Pakistan And Canada", INFCIRC/135, November 13, 1969. Zia Mian, "Some Issues Associated with Pakistan's Karachi Nuclear Power Plant (KANUPP)," *Sustainable Development Policy Institute* (2000).

[52] International Atomic Energy Agency, "The Texts of the Instruments Concerning the Agency's Assistance to Pakistan in Connection with the Establishment of a Nuclear Power Reactor Project", INFCIRC/116, September 6, 1968, and INFCIRC/116/Add.1., October 8, 1971; Salim Khan, M.Saeed Mulla, Sohail Qayyum, "IAEA Safeguards in Pakistan and Emerging Issues/Challenges", IAEA-CN-184/77, Proceedings of the Symposium on International Safeguards: Preparing for Future Verification Challenges, November 01-05, 2010, Vienna, Austria, <https://inis.iaea.org/collection/NCLCollectionStore/_Public/42/081/42081520.pdf>.

activities and become self-sufficient in NW production. Pakistan constructed a fuel-fabrication plant, and several reprocessing facilities—one of which was developed via a French-Pakistani-IAEA tripartite cooperation and a tripartite safeguards agreement.[53] However, safeguards were never implemented at the plant, and when France withdrew from the cooperation, Pakistan completed the plant on its own in the early 2000's. By this time, the plutonium route originally chosen by Pakistan had long been pre-empted by enrichment efforts. In 1973, Pakistani metallurgist Abdul Qadeer (A.Q.) Khan stole information on uranium centrifuges from the Netherlands.[54] The information was transferred to Pakistan, enabling the state to pursue the uranium route. In the 1990s, Pakistan produced a crude VHEU NW design with help from China. A.Q Khan eventually provided VHEU, but it was the Pakistan Atomic Energy Commission developed several indigenous weapon designs that were tested in May of 1998.[55] The first test or tests, declared by Pakistan on May 28, were generally thought to have been uranium based. There is disagreement about the fissile material in the May 30 test, and it is reported that it may have been all plutonium or a composite of uranium and plutonium. The only domestic source of plutonium at the time was KANUPP, suggesting some parallel efforts in both uranium and plutonium. Pakistan has since established a new centrifuge facility in Kahuta. Program activities continued, with new reactors and reprocessing plants being built and bomb designs being developed long after the initial successful uranium NW efforts.[56]

With respect to NW delivery, Pakistan has considered aircraft and short-range missiles.[57] Pakistan has also played a key role in nuclear proliferation by transferring sensitive uranium enrichment technology to other countries such as Iran, Libya, and North Korea via the Khan network.[58]

---

[53] International Atomic Energy Agency, "The Text of The Safeguards Agreement of 18 March 1976 Between the Agency, France And Pakistan", INFCIRC/239, June 22, 1976.
[54] Gordon Corera, *Shopping for Bombs: Nuclear Proliferation, Global Insecurity, and the Rise and Fall of the A. Q. Khan Network*, (Oxford: Oxford University Press, Incorporated, 2006).
[55] Dana Priest, "U.S. Labs at Odds on Whether Pakistani Blast Used Plutonium", *The Washington Post*, January 17, 1999; Feroz Khan, *Eating Grass: The Making of the Pakistani Bomb*, (Redwood City: Stanford University Press, 2012), pp. 174-190.
[56] Zia Mian, A.H. Nayyar and R. Rajaman, "Exploring Uranium Resource Constraints on Fissile Material Production in Pakistan", *Science & Global Security,* vol. 17, no. 2-3 (2009), pp. 77-108.
[57] "Country profile: Pakistan, Missile", Nuclear Threat Initiative, November 2019, <https://www.nti.org/analysis/articles/pakistan-missile/>.
[58] David Albright & Corey Hinderstein, "Unraveling the A. Q. Khan and future proliferation networks", *The Washington Quarterly,* Vol. 28, no. 2 (2005), pp. 109-128.

3.4.2 The Democratic People's Republic of Korea (DPRK)

Yongbyon is the center of the DPRK's nuclear program.[59] Its IRT-2000 research reactor and its fuel was procured from the USSR in the early 1960s, and uranium deposits in the country were explored at the same time.[60] An indigenously designed graphite-moderated Magnox reactor began operation in 1986.[61] Over the coming years, the DPRK invested in reprocessing and fuel fabrication capabilities.[62] International concerns about the DPRK's capabilities grew, and the country was pressured to join the NPT in 1985 by the USSR, which offered to provide the DPRK with additional nuclear power reactors if it joined.[63] A first safeguards agreement with the IAEA was signed in April 1992, and activities were initiated to confirm the state's initial nuclear inventory. Verification of the initial declarations failed when the IAEA found evidence that the DPRK had processed plutonium contrary to its declarations.[64] The DPRK has developed a new uranium mine, a uranium milling facility, waste facilities and a facility capable to convert uranium ore into uranium dioxide.[65] During the 1990s, the DPRK received assistance in developing enrichment technology through the Khan network as early as 1998.[66] The DPRK withdrew from the NPT in 2003. In the early 2000's, concerns grew about production of HEU, partly due to the construction of a covert uranium enrichment facility later observed in 2010.[67] The facility was pilot scale, suggesting that the plutonium program (limited by its reactor capacity) was being replaced by a uranium enrichment program able to produce many times more warheads than the plutonium route. In 2005, the DPRK announced successful development of NWs, and the first test explosion took place the following year. The full extent of the DPRK's NWP is still

---

[59] Robert S. Norris, and Hans M. Kristensen, "North Korea's Nuclear Program, 2005," *Bulletin of the Atomic Scientists,* Vol. 61, no. 3 (2005), pp. 64-67.

[60] "North Korea Nuclear Overview", Fact sheet, Nuclear Threat Initiative, October 11, 2018, <https://www.nti.org/analysis/articles/north-korea-nuclear/>.

[61] Grant E. Christopher, Robert Gregg, and Christopher Grove, "North Korean Fissile Material: A New Model," *Proceedings of the INMM & ESARDA Joint Annual Meeting*, May 22-26, 2023, Vienna.

[62] Christopher, Gregg and Grove, "North Korean Fissile Material: A New Model."

[63] François Carrel-Billiard and Christine Wing, "North Korea and the NPT", *Nuclear Energy, Nonproliferation and Disarmament,* April 2010, <https://www.ipinst.org/wp-content/uploads/2010/04/pdfs_koreachapt2.pdf>.

[64] Vitaly Fedchenko ed., *The new nuclear forensics, Analysis of Nuclear Materials for Security Purposes*, (Stockholm International Peace Research Institute, Oxford University Press, 2015), p. 243.

[65] Carrel-Billiard and Wing, "North Korea and the NPT."

[66] "North Korea Nuclear Overview," Nuclear Threat Initiative.

[67] Charles Day, "Visiting North Korea: Q&A with Siegfried Hecker", *Physics Today*, February 23, 2011, <https://pubs.aip.org/physicstoday/Online/1499/Visiting-North-Korea-Q-A-with-Siegfried-Hecker >.

unknown, and the extent of the enrichment program has been debated The DPRK has also put efforts into short range and intermediate range missiles to deliver early NWs.[68]

3.4.3 Iraq

Iraq signed the NPT in 1968, but is believed to have already had plans for a NWP at that time.[69] The first nuclear acquisition was a French light-water reactor (Tammuz-1or Osirak) installed at the Tuwaitha site. With time, the Tuwaitha site was expanded with assistance from Italy, which delivered radiochemical, radioisotope production, chemical engineering, material testing laboratories and a fuel fabrication facility.[70] In 1981, the Osirak reactor was bombed by Israel, but many surrounding facilities, like the pilot-scale reprocessing laboratories, were not damaged.

Determined to produce a NW, Iraq initially tried to replace the reactor, and in parallel pursued uranium enrichment. Replacing the reactor proved difficult and time-consuming, but Iraq continued research on plutonium separation for many years. Iraq then shifted its NW program to uranium enrichment and devoted all its resources to this method. Iraq had sufficient uranium resources from open market purchases. There was also a large and successful project to extract uranium from phosphate fertilizers Iraq first decided to go with Electromagnetic Isotope Separation (EMIS) developed in the US before World War II. The EMIS program consumed many resources and progressed slowly; chemical enrichment, gaseous diffusion and gas centrifuges were also explored.[71] Iraq acquired centrifuge design information from several rogue German scientists, but notably not from the Khan network. [72] Efforts were slow nonetheless, and in 1990 the Iraqi leadership ordered diversion of safeguarded HEU research fuel for the NWP. Following the Gulf War and the UN Security

---

[68] Hans M. Kristensen, and Matt Korda, "North Korean nuclear weapons, 2021", *Bulletin of the Atomic Scientists,* Vol. 77, no 4 (2021), pp. 222-236.

[69] "Iraq Nuclear Chronology", Nuclear Threat Initiative, February 2009, <https://www.nti.org/wp-content/uploads/2021/09/iraq_nuclear.pdf>.

[70] "Iraq Nuclear Chronology," Nuclear Threat Initiative; US Central Intelligence Agency, Directorate of Intelligence, "The Iraqi Nuclear Program: Progress Despite Setbacks - An Intelligence Assessment," Vol 872 (1983),< https://nsarchive2.gwu.edu/NSAEBB/NSAEBB82/iraq19.pdf>.

[71] "Iraq Nuclear Chronology," Nuclear Threat Initiative; Wisconsin project on nuclear arms control, "Iraq's Nuclear Weapon Program Profile", January 1 (1999), <https://www.wisconsinproject.org/iraqs-nuclear-weapon-program-profile/>.

[72] Institute for Science and International Security, "Iraq's Acquisition of Gas Centrifuge Technology, Part II: Recruitment of Karl Heinz Schaab," <https://exportcontrols.info/centpart2.html>.

Council Resolution 687 to ensure Iraqi compliance on the destruction of NW facilities, a comprehensive series of on-site inspections were conducted by the United Nations Special Commission (UNSCOM) and the IAEA, which revealed an extensive clandestine program.[73] Iraq mainly considered missiles with ranges appropriate for nearby countries as delivery systems.[74]

3.4.4 Iran

Iran showed an early interest in nuclear energy, and a nuclear research center was established at Tehran University in the late 1950's. In 1967, a pool-type research reactor from the US, fueled with HEU, was installed at the center.[75] Iran signed the NPT as it opened for signature and planned for commercial nuclear power using foreign vendors. In the mid-1970's, Iran bought a share of the French EURODIF uranium enrichment plant, but never received any output. Iran also initiated uranium prospecting using French assistance.[76] Deals were made with South Africa and later Namibia to buy yellow-cake, and efforts were invested in building up domestic nuclear competence. The ambitious nuclear plans were abandoned after the Islamic Revolution in 1979.[77] In the late 1970's, US intelligence received indications of a clandestine NWP.[78] In the coming two decades, Iran expanded its nuclear cooperation ambitions resulting in e.g., the indigenous construction of a heavy-water production facility, acquisition of uranium enrichment technology, and plans for fuel fabrication and uranium conversion using foreign vendors. Iran also engaged with A.Q. Khan, whose assistance was crucial to the rapid success of its centrifuge enrichment program.[79]

---

[73] Fourth consolidated report of the Director General of the International Atomic Energy Agency under paragraph 16 of Security Council resolution 1051 (1996) UN Security Council, Letter Dated October 6, 1997 from the Director General of the International Atomic Energy Agency to the Secretary-General. S/1997/779. 1997.

[74] "Iraq's Weapons of Mass Destruction Programs", Director of Central Intelligence, October 2002, <https://irp.fas.org/cia/product/Iraq_Oct_2002.pdf>.

[75] "Iran Nuclear Overview", Nuclear Threat Initiative, June 25, 2020, <https://www.nti.org/analysis/articles/iran-nuclear/>.

[76] "Iran Nuclear Chronology", Nuclear Threat Initiative, May 2011, <https://media.nti.org/pdfs/iran_nuclear.pdf>.

[77] "Iran Nuclear Chronology", Nuclear Threat Initiative.

[78] "Iran Nuclear Chronology", Nuclear Threat Initiative.

[79] "Iran Nuclear Chronology", Nuclear Threat Initiative.

In 2002, a dissident group revealed the existence of two, previously unknown, sites.[80] One site was intended to house a 40 MWth heavy-water research reactor at Arak, similar in design to the plutonium producing reactors in India, Pakistan, Switzerland and Israel, but its actual construction had not begun. Iran approached Russia for design assistance with the Arak heavy water reactor, but was instead offered help in producing light water reactor fuel. Construction of the reactor continued at a slow pace, leading it to lag behind the centrifuge program. Plans to complete and operate the reactor were given up in agreeing to the Joint Comprehensive Plan of Action (JCPOA), and the reactor's calandria was filled with concrete. The Arak project consisted of three elements: a heavy water plant completed in the early 2000s, a heavy water reactor nearing completion by 2015, and a reprocessing plant that, according to available information, never existed even in design form. Hence, it appears that Iran pursued the plutonium route and invested in two of the three elements, but not in reprocessing, which would have been the final essential element. The second site was a gas centrifuge enrichment site at Natanz in advanced stages of construction, designed to hold up to 50,000 centrifuges offered by A.Q. Khan.[81] This suggests that by 2003, most effort was concentrated on the uranium route. There is little indication of large-scale R&D, let alone the construction of a reprocessing plant, to recover plutonium from the planned reactor although Iran admitted to plutonium separation activities on a laboratory scale prior to 1993.[82] The discoveries in the early 2000's put international pressure on Iran to halt its nuclear developments. Following negotiations, Iran stated in 2003 that it would sign the Model Additional Protocol (AP) and suspend conversion and enrichment activities. The AP was never ratified, and enrichment and heavy water production were ongoing by 2006. In 2011, a second enrichment site at Fordo started operation.

The IAEA issued the first alleged description of the Iranian NWP and diplomatic negotiations intensified.[83] Iran signed the Joint Plan of Action (JPOA) in 2013 and the more intrusive JCPOA in 2015, which ended the heavy-water reactor project. Iran accepted more frequent inspections,

---

[80] "Information on Two Top Secret Nuclear Sites of the Iranian Regime (Natanz & Arak)", *Iran Watch*, Private viewpoints, December 1, 2002, <https://www.iranwatch.org/library/ncri-info-2-top-secret-nuclear-sites-12-02>.

[81] Robert Kelley, "Nuclear Programs in the Islamic Republic of Iran as of 2021", in *2021 Yearbook North Korea Nuclear Program - Weapon-Policy-Technology*, KINAC/GP-001/2021, pp. 208-232

[82] Report by the Director General, "*Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*", GOV/2004/83, November 15, 2004.

[83] "Iran Nuclear Overview," Nuclear Threat Initiative.

additional safeguards measures, a scale-back of enrichment activities and a redesign of the Arak research reactor.

4. Analysis

In this section, we analyze the countries from a number of different perspectives to highlight show how the choice of the fissile material route was impacted. An overview of the preferred fissile material route in the selected countries is shown in Table 1.

Table 1. Summary of the ten states investigated in this work. Columns two and three indicate the routes pursued in the early exploratory phase, while column four provides the rationale for the chosen route(s).

State	VHEU	Plutonium	Material choice motivation
United States	X	X	Both routes. No one path was known to be more successful so both paths were explored.
Soviet Union	X	X	Both routes. Determined to master the same technologies as the US so both paths were explored.
South Africa	X		HEU route. Commercial incentives to sell uranium products motivated the uranium path.
Sweden		X	Pu route. Domestic uranium resources and reactor competence motivated this choice.
Israel		X	Pu route. Foreign collaborations enabled this focus. France provided reprocessing.
India		X	Pu route. Civilian breeder fuel cycle. USA provided reprocessing assistance.
Pakistan	X	X	Pu route → Both routes as A.Q. Khan opened up the uranium option. U route dominated until Pakistan came back to Pu route in the late 1990s. France provided reprocessing.
DPRK	X	X	Pu route → Both. A.Q. Khan opened up the uranium option. Currently, the focus on Pu seems low. Former Soviet Union provided reprocessing assistance.
Iraq	X	X	Pu route → U route. Pu route abandoned after reactor bombing. Espionage assistance.
Iran	X	X	Both routes → U route. Uranium route became preferred due to massive assistance from Pakistan. No reprocessing R&D.

4.1 Availability of uranium resources

In some case studies, uranium resources have influenced a state to (potentially) explore a particular fissile material route. The early US and Soviet programs had access to uranium resources, which enabled both routes to be explored, but it did not lead to a preferred route. In South Africa, the domestic uranium resources had already motivated the development of civilian fuel cycle activities that could also be used for NW production, but it seems that the uranium resources per se were not important for the selection of the fissile material route. Sweden, India, Pakistan, Iran, Iraq and Israel all have some domestic uranium resources, but these do not seem to have been the reason for pursuing a specific fissile material route. Rather, the resources appear to have been sufficient to allow either route to be pursued. Pakistan has limited domestic uranium production. This constrains unlimited enrichment of uranium or production of fuel and targets for military reactors.[84] These constraints have not prevented Pakistan from building a significant weapon stockpile over four decades. We have no indication that uranium resources have affected the fissile material routes in Iran, Iraq, and Israel. Little is known about the DPRK uranium resources. Open-source publications all conclude that there are adequate domestic resources not to inhibit a NWP or any particular route.

4.2 International insight into the NWP

Early efforts to manufacture NWs in the US and Soviet Union required massive resources, but there was limited knowledge about the end goal. In retrospect, indicators and signatures of the NW manufacture probably could have been easily identified, but at the time such information was of interest only to the intelligence community. South Africa, Israel, India, and Pakistan have since openly established nuclear infrastructure intended for NWs, but have refrained from sharing the details of its intended use. Similarly, Israel's Dimona reactor was publicly known for decades, although its details are still unknown. Neither India nor Pakistan have tried to hide their nuclear installations, only their intended use. It was noted that India did not sign the NPT, but it was not known that they possessed NWs until the nuclear test in 1974. Initial nuclear activities in Pakistan were under limited safeguards but as the state expanded its nuclear activities, it became clear that Pakistan refused to apply adequate safeguards. In retrospect, it is well-known that Pakistan benefited from information stolen by A.Q. Khan, which is evidence of covert activities.

[84] Erik Branger, et al., "Plutonium Production under Uranium Constraint," *Science & Global Security*, Vol. 31, no. 3 (2023), pp. 115–136.

Other states, such as Sweden, the DPRK, Iraq, and Iran, tried to use civilian nuclear energy programs to mask military nuclear programs. Notably, none of the programs used civilian power reactors to acquire plutonium, relying instead on small reactors using natural uranium and heavy-water or graphite moderators. Sweden later abandoned such plans, while the DPRK withdrew from the NPT regime to pursue NWs. Iraq successfully kept its electromagnetic separation activities covert, while efforts to extract uranium from phosphates were known, and the gas centrifuge enrichment program was severely compromised by poor security. It was thus obvious that a uranium enrichment program was underway, but its level of success was unknown until post-war inspections. Iran's expansions in nuclear enrichment have progressed without any expansion of civilian power-producing reactors that can use the uranium, leaving little doubt that they are pursuing military activities.

In conclusion, there have been few surprises when certain states have revealed their NWPs, as such activities have often been preceded by suspicions although the details of the programs have been concealed. The findings suggest that there is no preferred fissile material route, covert or visible. Each case we have studied is highly dependent on unique situations in each state.

4.3 International relations

4.3.1 Foreign donor support and aid

The US differs significantly from the other states in this work as it was the first to develop NWs and could not rely on information about prior NW development. It is well documented that the Soviet Union developments were based on the American design. It was also not in the Soviet interest to assist other states in their NW development, but the Soviets gave extensive assistance, especially to China, for fuel cycle activities that could enable indigenous weapons development. South Africa could have relied on international expertise, but in practice developed an indigenous, inefficient enrichment process that was not copied by others.

Many other states initiated NW plans using foreign assistance to a varying degree, like Sweden. Other states bought facilities from abroad. Israel acquired a French heavy-water reactor and a reprocessing plant, India acquired the CIRUS reactor from Canada, Pakistan acquired a Canadian reactor and received considerable support from the IAEA to explore and use domestic uranium resources through the Technical Cooperation Program assistance. The DPRK relied on the Soviet Union for a pool-type reactor. Iraq relied on French assistance for the Osirak reactor, and stolen German information to develop gas centrifuges.

It seems that while an official reason is to build up expertise and prepare for civilian applications, foreign aid is a way to jump-start a NWP. The collaborations focused on natural uranium reactors, which avoided the need to share sensitive enrichment technology.

4.3.2 Espionage and proliferation networks

Espionage did not help the US develop its NWs, but it is known that the Soviet Union accelerated its NWP program with classified information from the Manhattan Project.[85] It is difficult to know if and to what extent Israel benefited from espionage, but it has been speculated that uranium from a US fuel manufacturing plant was diverted to the Israeli NWP.[86] Pakistan, the DPRK, and Iran are all known to have benefited from clandestinely obtained centrifuge technology through the Khan network and to have switched from the plutonium route to the uranium route as a result. These states de-emphasized the plutonium route after gaining access to uranium enrichment technology. Iraq received significant centrifuge design information from a small group of Germans, but notably not from the Khan network. In the cases of South Africa, Sweden, and India, there are no indications that either state relied on espionage or the use of proliferation networks in nuclear weapon development. However, the indigenous enrichment process developed in South Africa involved illicit sharing of centrifuge enrichment technology between German individuals and Libya, Brazil, and South Africa.[87]

4.3.3 Conflicts, attacks and military threats

In the 1940s, World War II was an important reason for developing NWs, as it was believed that the side that could master the development first would have the upper hand. There is no specific military threat or attack that motivated the development of NWs, and the Soviet development can be interpreted as a way to balance the power gained by the US in having NWs. The choice of a specific route is not believed to find an explanation

---

[85] Sarah Pruitt, "8 Spies Who Leaked Atomic Bomb Intelligence to the Soviets", *HISTORY*, August 18, 2021, <https://www.history.com/news/atomic-bomb-soviet-spies>.
[86] Victor Gilinsky & Roger J. Mattson, "Revisiting the NUMEC Affair," *Bulletin of the Atomic Scientists* 66, no. 2 (2010), pp. 61-75
[87] Erico Guizzo, "How Brazil spun the atom", *IEEE Spectrum*, March 1, 2006, <https://spectrum.ieee.org/how-brazil-spun-the-atom>.

in these two cases as it was most important that at least one of the chosen routes were successful.

For South Africa, Israel, Sweden, India, Pakistan and the DPRK, we find no evidence of armed conflicts or attacks influencing the choice of fissile material route. In the case of South Africa, the fissile material route was chosen before the conflict with Angola. And although Israel is surrounded by potentially hostile countries, there are no indications that this has impacted the choice of fissile material route. Sweden was not even involved in any armed conflicts or attacks at the time of NWs consideration. India shares borders with China and Pakistan and has been in involved in conflicts with both countries for a long time. However, the choice of the fissile material route seems again to have been based on other factors. For Pakistan, NW ambitions increased with the India's peaceful nuclear explosion, but we don't find that this impacted the fissile material route. Potentially, conflicts may have made Pakistan more receptive to offers from A.Q. Khan. The same can be said for the DPRK, which borders Russia and China (both of which are NWS) and shares a fortified boundary with South Korea. Although these conflicts do not seem to influence the fissile material route, they may have increased the motivation to quickly expand the more promising route.

For Iran and Iraq, the situation is different. In Iran, the 1979 Islamic Revolution was followed by the Iran-Iraq war. During this period, Iran ineffectively bombed Iraq's Tuwaitha nuclear research center, and Iraq bombed Iran's Bushehr nuclear power plant. As a result, Iran's nuclear efforts were largely on hold throughout the 1980s and only resumed around 1990, largely aided by Pakistan and A.Q. Khan. In Iraq, the 1981 bombing of the Iraqi Osirak reactor had a significant effect on the route pursued to develop NWs. The reactor proved impossible to replace and options for obtaining HEU uranium were explored with limited success, possibly because this route was a backup option that the state was well-prepared to explore.

4.4 Delivery system constraints

In the case of the US and the Soviet Union, there were not many constraints imposed by the early crude delivery systems. In South Africa, the delivery systems do not seem to have posed any limitations for the gun-type NWs developed. The gun weapons could also fit into Jericho missile warheads. Sweden had aircraft capable of delivering tactical nuclear weapons. We have no evidence that Israel, India and Pakistan were constrained by their delivery systems, although it cannot be excluded. Statements from the DPRK suggest that they are now developing smaller tactical NWs, which could impose size and weight constraints and indicate a preference for plutonium, but earlier delivery systems do not appear to have been constrained.[88] Iraq and Iran have considered ballistic missiles as delivery systems, and neither country appeared particularly constrained by this.

This suggests that the delivery mode for first generation weapons does not significantly impact the preferred fissile material route. Rather, it seems to have been an issue tied to the availability of each fissile material (number of plutonium reactors versus enrichment capability).

4.5 Effect of export control or nuclear safeguards measures

The US and the Soviet Union are special cases that were not affected by either regime, as their NW development predated both. South Africa was under international sanctions due to apartheid from 1962. This largely cut them off from international military and industrial commerce. However, their NWP was so primitive that most parts could be imported or developed domestically even under sanctions. Sweden's plutonium route was not impacted by either regime, although both made it clear that NW development was forbidden and later caused Sweden to abandon its NW ambitions. Israel obtained its initial nuclear infrastructure from France, circumventing export controls and nuclear safeguards on these facilities.

India's good relations with the US enabled nuclear trade with a large number of countries.[89] We don't find evidence to suggest that export control or safeguards measures determined the fissile material route. For Pakistan, export control and nuclear safeguards measures were problematic and made proliferation networks attractive. In that sense, the measures did impact the choice in a direction that was highly dependent on what was offered by the proliferation networks. The DPRK had no safeguards measures in place and was not allowed to engage in nuclear trade with other states. This explains why the equipment provided by the proliferation networks was vital. Iraq and Iran have implemented safeguards and used civilian motives as a cover for clandestine activities. In Iraq, export control measures made it difficult to import the desired equipment, but did not prohibit the selected route, as simple (old)

[88] "North Korea's Nuclear Weapons and Missile Programs", In focus report, Congressional Research Service, updated December 19, 2023, <https://sgp.fas.org/crs/nuke/IF10472.pdf >.

[89] Ian Stewart and Adil Sultan, "India, Pakistan and the NSG," King's College London, News centre, June 10, 2019.

equipment could be acquired. IAEA safeguards efforts were not sufficient to discover suspicious activities and facilities. Similarly, export control measures and the IAEA's limited safeguards mandate of verifying declared nuclear materials do not seem to have had a direct impact on the choice of fissile material route in Iran.

Although export control mechanisms and nuclear safeguards measures are in place to prevent the proliferation of nuclear materials, they are not always successful and there are examples where espionage has indirectly impacted the fissile material route. One example of this is the sharing of enrichment technology for LEU production purposes, by the UK with Germany and the Netherlands.[90] Although IAEA and EURATOM material safeguards measures were not designed to inhibit espionage that resulted in critical design information being shared with Pakistan and others via A. Q. Khan, and with Iraq via rogue German scientists and an inadequate export control framework at the time.

Export restrictions on reprocessing have been vitally important as several states have used illicit reprocessing technology to proliferate. India and Israel stuck to the plutonium route because of successful reprocessing at Prefre and Dimona. The DPRK initially used reprocessing as the basis for a NW program, as the technology was not effectively embargoed in the 1970s. Pakistan openly acquired French reprocessing technology in 1979, and this became the international basis for forbidding any further transfer of reprocessing technology. Note that Iran started the Arak project but gave it up, in the early 2000s, partially because of the lack of any reprocessing R&D. Export restrictions on uranium enrichment are much more difficult but urgently important. Gas centrifuges are easy to manufacture in a state with a moderately advanced mechanical engineering industry. Controls on dual-use items such as rotor materials, specialized valves, power supplies and sensors are only partially effective. The wide use of these items in many other fields makes controls difficult. The ease of hiding centrifuge activities is also a way to circumvent export restrictions.[91]

[90] Her Majesty's Stationery Office. "*Agreement Cmnd. 4793 between the United Kingdom of Great Britain and Northern Ireland the Federal Republic of Germany and the Kingdom of the Netherlands on Collaboration in the Development and Exploitation of the Gas Centrifuge Process for producing Enriched Uranium*", Treaty Series No. 69 (1971), Almelo, March 4, 1970.

[91] Lena Oliver, Jenny Peterson and Katarina Wilhelmsen, "Urananrikning med gascentrifugering En analys med fokus på exportkontroll", SKI Rapport, 44 (2005), pp. 33-38, <https://www.osti.gov/etdeweb/servlets/purl/20656548>.

5. Conclusion and outlook

We have investigated the factors that influence the choice of a particular fissile material route to NWs. For most states, the existence of uranium resources enabled military development of either type, and the fissile material route was more closely linked to existing nuclear infrastructure and competence in the state. The analysis suggests that the issue of international insight into the NW program plays a minor role for the fissile material route. None of the countries managed to successfully hide their activities and avoid suspicion from the international community, but this did not impact the chosen route. International relations appear more important. The nature of these relations made it possible (or impossible) to pursue a chosen fissile material route because they enabled or prevented the acquisition of equipment and know-how through official programs such as Atoms for Peace. Technology sharing has primarily concerned nuclear reactors and excluded reprocessing technology, with a few exceptions—the proposed sale of a reprocessing plant from France to Pakistan in 1976, and France's export of a fuel fabrication plant, reactor, and reprocessing plant to Israel. The main donor states were the US, the Soviet Union, Canada, and France. Examples of states that attempted to use this technology to clandestinely produce plutonium included Pakistan, Iraq, and the DPRK, as well as India, which misused reactor and reprocessing technology for a nuclear explosion in 1974. International outrage at this proliferation led to stricter export controls on nuclear transfers. Espionage and proliferation networks were a decisive factor, and in several cases re-directed the fissile material route. This was the case for Iraq which acquired centrifuge technology from a handful of German individuals, and for Pakistan, Iran, Libya, and the DPRK, all of which illicitly acquired information on uranium enrichment. Export controls and safeguards measures have sometimes made it difficult for states to pursue a chosen route, and proliferation networks have then become more important. Constraints related to the military delivery systems do not appear to play a major role. We found no evidence that any state selected its fissile material route based solely on the delivery systems available. For most states, delivery systems have been adapted to the type of NWs developed.

One conclusion is that the plutonium route becomes less attractive if the reprocessing technology is under strict international control, which includes mandatory reporting of activities that are currently voluntary (such as flow-sheet verification relating to reporting quantities of separated neptunium and americium in states with a Comprehensive

Safeguards Agreement).[92] In addition, it is necessary to ensure that the entire supply chain for such technology is considered under strict export control. Many countries have plans for new nuclear power, and states are receiving assistance to build civilian nuclear infrastructures under turn-key conditions. Diversion of high burn-up reactor fuel by countries without reprocessing capabilities poses little risk if the state has no motivation for a breakout scenario. Reprocessing is currently available in a few countries, most of which are NWSs. In Russia, India and Pakistan, it is a government monopoly under strict controls and with little or no IAEA verification. There are a few examples of reprocessing facilities operated by states that do not possess NWs. One recent exception is Japan, which operates the Rokkasho reprocessing plant under IAEA verification. Here, it is important to ensure low uncertainties in verification measurements and a holistic safeguards approach to ensure that there is no separation of plutonium for NW use. Although it is difficult to conceal diversion of fissile material from civilian applications, more abundant reprocessing activities may increase the risk.

It is more difficult to prevent the misuse of enrichment technology. Although attempts have been made, they have not been successful. Gas centrifuges can be very simple devices that can be mass-produced, and many states can build them. While centrifuge enrichment is difficult to detect from a distance, indicators from the export control community on specialized raw materials and equipment could prove to be useful indicators. Looking ahead, proliferation in 2025 should be focused on VHEU production using gas centrifuges. This process can best be monitored by National Technical Means,[93] which are monitoring techniques used to verify compliance with international treaties, open-source information, and information generated by export control experts.[94]

---

[92] P. Rance, et al., "Neptunium flow-sheet verification at reprocessing plants". Proceedings of GLOBAL 2007 conference on advanced nuclear fuel cycles and systems, La Grange Park (United States), ANS, 13 Sep 2007, pp 346–352.

[93] Melvin R. Laird, *Memorandum for Assistant to the President for National Security Affairs, Subject: Revelation of the Fact of Satellite Reconnaissance in Connection with the Submission of Arms Limitation Agreements to Congress*, June 8, 1972. <https://nsarchive2.gwu.edu/NSAEBB/NSAEBB231/doc02.pdf>;
R.A. Scribner, T.J. Ralston, W.D. Metz, "National Technical Means," in *The Verification Challenge*, (Birkhäuser, Boston, MA, 1985), pp. 47-66.

[94] Melvin R. Laird, *Memorandum for Assistant to the President for National Security Affairs*; Scribner, Ralston, Metz, "National Technical Means."