The Nuclear Fuel Cycle and the Proliferation “Danger Zone”

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ABSTRACT
Horizontal nuclear proliferation presents what is sometimes referred to as the “Nth country problem,” or identifying which state could be next to acquire nuclear weapons. Nuclear fuel cycle technologies can contribute to both nuclear power generation and weapons development. Consequently, observers often view civilian nuclear programs with suspicion even as research on nuclear latency and the technological inputs of proliferation has added nuance to these discussions. To contribute to this debate, I put forth a simple theoretical proposition: En route to developing a civilian nuclear infrastructure and mastering the fuel cycle, states pass through a proliferation “danger zone.” States with fuel cycle capabilities below a certain threshold will likely be unable to proliferate. States that pass through the “danger zone” without proliferating will be unlikely to do so in the future. I support this proposition by introducing preliminary analysis from the Nuclear Fuel Cycle (NFC) Index, a new heuristic tool to complement political assessments of the connection between civilian nuclear energy development and nuclear weapons proliferation. I conclude with policy implications for contemporary Iran, Saudi Arabia, Japan, and South Korea. Taken together, this article calls for increased policymaker interaction with historical cases and more sophisticated academic engagement with the nuclear fuel cycle.

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Introduction
Nuclear proliferation is among today’s foremost international security challenges. The Democratic People’s Republic of Korea’s (DPRK) six nuclear test explosions and the at times hostile rhetoric between Supreme Leader Kim Jong-un and US President Donald J. Trump underscore the seriousness of the proliferation threat (Choi 2018; Yanagisawa 2019; Zhang and Wang 2019). While North Korea has diverged from peaceful uses of nuclear energy, many other states with nuclear technologies have not done so. The International Atomic Energy Agency (IAEA) lists 220 operational nuclear research reactors in 53 countries (IAEA 2020d) and 442 power reactors in 30 countries (IAEA 2020c). From 1939–2012, 31 countries had uranium enrichment or plutonium reprocessing (ENR) capabilities, presenting two pathways for acquiring nuclear weapons (Fuhrmann and Tkach 2015). Yet, only nine states currently possess nuclear weapons.
(Kristensen and Norris 2017), and only one other – South Africa – successfully built and then abandoned the bomb. Consequently, it is important to have a clear-eyed view of the fuel cycle and the risk factors associated with various levels of civilian nuclear technology development¹.

Observers of nuclear politics have pinpointed the Middle East and East Asia as the most likely regions for horizontal nuclear proliferation. The Islamic Republic of Iran appeared to turn the page on its history of clandestine facilities and past military nuclear research with limitations on – and increased monitoring of – its nuclear program in the 2015 Joint Comprehensive Plan of Action (JCPOA), also known as the Iran Nuclear Deal (Mousavian and Mousavian 2018; Tabatabai and Esfandiary 2018). However, the Trump administration’s decision to exit the deal and subsequent Iranian threats of increased ENR activities have again raised concerns about Tehran’s nuclear ambitions (Gordon 2019). Crown Prince Mohammed Bin Salman (2018) of the Kingdom of Saudi Arabia has warned, “[I]f Iran developed a nuclear bomb, we will follow suit as soon as possible.” His statement has triggered increased scrutiny of efforts to construct the Kingdom’s first research reactor and secure a Section 123 civilian nuclear cooperation agreement with the United States that permits uranium enrichment (Miller and Volpe 2018; Sokolski and Tobey 2018). In East Asia, Japan and South Korea face security threats from the DPRK alongside questions about Trump’s willingness to defend these longstanding US allies falling under the nuclear umbrella (Yoshida 2018). There are resultant concerns about these states potentially pursuing nuclear weapons to protect themselves, especially given their scientific and technical capabilities (Debs and Monteiro 2018).

Despite their stated interest in solely peaceful uses of nuclear technology, the focus on each of these states highlights the dichotomy of the nuclear age. Indeed, the same uranium enrichment capabilities used to power nuclear reactors and generate electricity, or produce medical radioisotopes, can also manufacture weapons-grade highly-enriched uranium (HEU). This problem is not confined to the enrichment process, as fuel cycle technologies are inherently dual-use, and normal nuclear reactor operations produce plutonium that could also be used in weapons production after reprocessing. Moreover, technical pathways to the bomb are hardly a secret in the contemporary era; basic design parameters can be found in open-source literature².

Further complicating the picture is Article IV of the Treaty on the Nonproliferation of Nuclear Weapons (NPT). It grants each of the States Parties the “inalienable right” to peaceful uses of nuclear technology “without discrimination” (NPT 1968). However, suspicion of the motives of some States Parties remains strong among many analysts and policymakers. Whether such skepticism is justified remains an open question, and opinions vary among analysts on a case-by-case basis. However, there is research suggesting that ties between civilian nuclear energy programs and military nuclear weapons programs may often be exaggerated (Miller 2017).

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¹ Strong advocacy by pro-nuclear organizations for the use of nuclear power as a means to replace fossil fuels and mitigate the effects of human-induced climate change further highlights the necessity of understanding the energy–weapons nexus (Baron and Herzog, forthcoming).

² Additive manufacturing could amplify this challenge in the future. Experts have accordingly drawn attention to the need to guide 3-D printing in the nuclear field toward greater dual-use distinguishability as this emerging technology develops (Kroenig and Volpe 2015; Hoffman and Volpe 2018; Volpe 2019).
Still, the more developed a country’s fuel cycle, the more a head start it will have should its political leaders decide to develop the bomb. Thus, it is critical to assess the relationship between fuel cycle mastery and proliferation. What is the likelihood that a state will proliferate after it has attained certain levels of civilian nuclear development?

To answer this question, I introduce the Nuclear Fuel Cycle (NFC) Index, a new heuristic tool to complement political assessments of the connection between civilian nuclear energy development and nuclear weapons proliferation. I use the NFC Index to evaluate a simple theoretical proposition: En route to developing a civilian nuclear infrastructure and mastering the fuel cycle, states pass through a proliferation “danger zone.” States with fuel cycle capabilities below a certain threshold will likely be unable to proliferate. States that pass through the danger zone without proliferating will be unlikely to do so in the future. Preliminary analysis supports this proposition and illuminates aggregate levels of nuclear technology development that have historically been most likely to coincide with proliferation, and those that have usually been associated with forbearance. The results suggest the need for increased policymaker interaction with historical cases and more sophisticated academic engagement with the nuclear fuel cycle.

**Nuclear Proliferation and Nuclear Latency**

To assess the potential connection between peaceful nuclear technology development levels and proliferation, it is important to take stock of current literature. Early post-Cold War scholarship elucidated the demand-side of nuclear proliferation following the collapse of the bipolar world order (Mearsheimer 1990; Deutch 1992; Frankel 1993). Sagan (1996–1997) also contributed to this moment by expanding the conversation on proliferation incentives beyond security. Scholars have gone on to develop theoretical frameworks based on security (Monteiro and Debs 2014; Debs and Monteiro 2017), domestic politics (Solingen 2007), and national identity concepts/international status aspirations (Hymans 2006) as drivers of horizontal proliferation. Many recent scholarly contributions draw on newly available archival documents, statistical methods, and formal models to better systematize nuclear proliferation research.

Experts generally point to security threats as the primary factor that might motivate proliferation by Iran, Saudi Arabia, Japan, or South Korea. However, even if there are multi-causal explanations for nuclear choices, political decisions alone cannot produce the bomb. A total of 26 states – ranging from Libya to Sweden – attempted to develop nuclear weapons, or explored this possibility, but never successfully proliferated (Müller and Schmidt 2010). While some states concluded that nuclearization was not in their national interest, others found it difficult to marshal resources to build the bomb (Hymans 2012; Montgomery 2013). Primitive weapon designs may be available in open sources, but states must also procure requisite weapons-grade fissile materials to sustain a nuclear chain reaction. Obtaining a “significant quantity” (IAEA 2002, 19) of 25 kilograms of isotope uranium-235 content in 90% HEU, or 8 kilograms of plutonium, is not an easy task. Still, the dual-use nature of nuclear technologies has sometimes led interested players in the international community to question civilian fuel cycle

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advancements that might enable fissile material production\(^4\). Countries accused of diversion may face dire consequences through diplomatic shaming, economic sanctions, or even military intervention.

Many scholars justifiably recognize the importance of technology in proliferation, leading to a focus on the supply-side. Fuhrmann (2009, 2012) explores the linkage between peaceful civilian nuclear cooperation and proliferation. Kroenig (2009a, 2009b, 2010) investigates motivations behind sensitive nuclear technology transfers. And Gheorghe (2019) analyzes the oftentimes permissive commercial dynamics of the global nuclear market that may enable proliferation. These causal pathways may contribute to horizontal proliferation, but they are not in themselves determinative. Singh and Way (2004), and Jo and Gartzke (2007), offer a potentially complementary approach by looking at statistical correlates of proliferation. Each study tests broad external, domestic political, and – most important for this article – technological factors to assess their cross-national association with proliferation. While these assessments are a step in the right direction, there are legitimate reasons to be skeptical of using generalized measures like Composite Index of National Capability (CINC) scores for understanding the technical inputs of nuclear proliferation.

Jo and Gartzke (2007) include a more sophisticated index in their regression analyses to measure latent nuclear weapons production capability. This index draws on seven variables from the nuclear capability indicators identified by Meyer (1984) and Stoll (1996): uranium deposits, metallurgists, chemical engineers, nuclear engineers/physicists/chemists, electronic/explosive specialists, nitric acid production capacity, and electricity production capability. These specific variables, however, do not necessarily reflect dual-use nuclear fuel cycle capabilities so much as they showcase a base of skills and equipment that could be used in a weaponization attempt. That is, they tell us little about how overall levels of peaceful nuclear development relate to proliferation. Further, Montgomery and Sagan (2009), and Sagan (2011), have demonstrated that using these types of quantitative variables does not always accurately predict historical proliferation.

Fuhrmann and Tkach (2015) have made strides to improve discussions about the intersection between military and civilian nuclear technologies by introducing a nuclear latency dataset. The authors provide a comprehensive list of ENR facilities from 1939–2012. However, their measure of latency is binary; they label 31 countries as potential proliferators during this period if they developed even a single, small-scale experimental ENR facility. Having a facility does not always indicate mastery of a technology, as evidenced by Iraq’s and Libya’s failures to build the bomb (Hymans 2012; Braut-Hegghammer 2016) despite their inclusion as latent nuclear states. To their credit, Fuhrmann and Tkach (2015) identify that the achievement of latency is a more common phenomenon than proliferation. There is certainly room to build upon this analysis by, for example, examining fuel cycle development progress both qualitatively and quantitatively.

Nuclear latency is a perplexing phenomenon. Even well-equipped intelligence agencies have failed to accurately assess the efficacy of fuel cycle facilities (Bollfrass 2017). Additionally, many states that develop capabilities enabling a drive toward the bomb

\(^4\)Survey experimental research suggests that a psychological connection between civilian and military nuclear technologies may also be present in the public consciousness (Baron and Herzog, forthcoming).
never actually proliferate, while a select few do so. It is critical to remember that ENR facilities have peaceful uses for electrical power generation and medical isotope production (among others), sometimes allowing proliferators to conceal their ambitions or delay nuclearization decisions (Mehta and Whitlark 2017). Some states may simply lack political drivers for proliferation such as vulnerability vis-à-vis a powerful enemy (Monteiro and Debs 2014; Debs and Monteiro 2017). Others may be content to engage in coercive diplomacy through possession of a “virtual arsenal,” perhaps deterring (Fuhrmann and Tkach 2015; Fuhrmann 2017) or compelling (Volpe 2017) rivals with veiled threats of nuclear proliferation. And states that fear consequences in the global economy if they proliferate (Solingen 1994) may have good reasons to settle for nuclear threshold status. Indeed, historical evidence shows that civilian nuclear energy programs infrequently lead to the bomb and may even contribute to forbearance. Such programs often draw international scrutiny, and proliferation attempts would likely jeopardize a state’s access to the nuclear supply chain – essential to the success of civilian nuclear power (Miller 2017, 2018; Gibbons 2020).

Direct reading of extant literature would advise analysts of nuclear proliferation to maintain a watchful eye over the political environments of dozens of states with ENR capabilities, regardless of the promises of NPT Article IV. However, national threat assessments, status conceptions, and interstate diplomacy are often subject to classification and willful misrepresentation. Such is the nature of international security, one of “unknown unknowns.” I propose that it is possible to improve predictions by focusing on aggregate national fuel cycle development levels. Below a certain capability threshold, states will likely be unable to proliferate. States that achieve a high level of nuclear fuel cycle mastery without proliferation will have foregone many opportunities to build the bomb. The baseline risk of proliferation for these countries is likely fairly low. Thus, I contend that it is important to pay careful attention to those states with a medium level of nuclear development. Historically, this middle ground forms the danger zone for proliferation where latency and hedging may interact.

**A Snapshot of Historical Nuclear States**

**Scope Conditions**

Today, nine countries possess a total of approximately 15,000 nuclear weapons (Kristensen and Norris 2017). The original five NPT-designated nuclear-weapon states (NWS) – China, France, Russia, the United Kingdom, and the United States – sought the bomb prior to embarking on full-scope peaceful nuclear programs. There were no international agreements to limit their ambitions. The three “de facto” NWS of India, Israel, and Pakistan declined to join the NPT and developed nuclear weapons outside the constraints of the nonproliferation regime. North Korea worked toward nuclear weapons prior to – and even after – its NPT accession in 1985 and conducted its first nuclear explosive test in 2006 after abandoning the Treaty. South Africa acceded to the NPT in 1991 after making internal plans to voluntarily dismantle its nuclear weapons program. Belarus, Kazakhstan, and Ukraine inherited nuclear arsenals after the Soviet Union’s dissolution, but they had limited physical control or access to launch codes and joined the
NPT alongside repatriating the weapons to Russia (Mearsheimer 1993; Budjeryn 2015, 2016; Rublee 2015).

Despite some setbacks, the 1968 NPT codified a powerful norm of nuclear forbearance and some scholars have even identified a causal effect of participation on states’ nuclear status (Fuhrmann and Lupu 2016). The Treaty distinguishes between the NWS and the non-nuclear-weapon states (NNWS) prohibited from developing nuclear weapons. The pursuit of nuclear weapons thus became riskier following the introduction of the NPT and its verification measures via the spread of IAEA safeguards per its Article III (NPT 1968). In addition, the Agency became organizationally effective at processing disclosures from national intelligence agencies (Carnegie and Carson 2019). With increased political costs, proliferation attempts steadily declined. A total of 24 of 58 economically-capable states engaged in nuclear weapons activities prior to the NPT opening for signature, but only 13 of 83 did so after its introduction (Müller and Schmidt 2010). Most importantly, in a world with a robust nonproliferation norm, the pursuit of nuclear weapons had to be disguised as peaceful uses of nuclear energy. The international community viewed with skepticism the ambitions of states that developed nuclear programs lacking in commercial or industrial viability.

To contribute to discussions on today’s proliferation challenges, the intent of this article is to identify the historical minimum and maximum thresholds of civilian nuclear energy development that supported nuclear weapons acquisition. With this as my objective, I focus on the era following the opening for signature of the NPT in 1968. Since the conclusion of the NPT and the globalizing of the role of the IAEA safeguards regime, it has become increasingly difficult to pursue nuclear weapons in the manner of the five NPT-designated NWS. Three types of states can thus help experts to identify what I refer to as the technological danger zone for proliferation. For several states in each category, I calculate the NFC Index, a quantitative measure of civilian nuclear development discussed in detail later in this article.

The first group of states is those that succeeded in building nuclear weapons. Studying these countries allows me to assess the lowest and highest levels of fuel cycle infrastructure at the time of clear nuclear weapons acquisition. The second group comprises states that, despite signing the NPT, have unsuccessfully pursued nuclear weapons or have been suspected of doing so under the cover of peaceful uses of nuclear energy. Looking at their NFC Index enables a determination of how these states had progressed relative to the first group before actual or suspected military nuclear activities were terminated. The third group is states that embraced the norm of the NPT and have not attempted to develop nuclear weapons after doing so. Analyzing such cases is important because it highlights trends related to NPT membership. Indeed, some of these states joined the NPT before embarking on a large-scale nuclear energy program, and others only joined after attaining high levels of fuel cycle mastery.

The NFC Index offers an aggregate score for the qualitative and quantitative sophistication of a country’s nuclear fuel cycle in a given year. It draws on publicly-available data to assess a country-year point value: IAEA (2009, 5) guidance regarding facility scale of operations, numerous technical databases, and historical country profiles. The Index, therefore, takes into account the different elements in a state’s civilian nuclear program as well as operating experience and the potential for fissile material accumulation. Selecting a date for calculating a given state’s NFC Index is not always straightforward. For
a concept validation exercise, it is essential to select meaningful cases to infer general results without treating each case as an individual event. There may be unexpected outliers in the past or the future – as the pursuit of the bomb is ultimately a political decision – but time-stamped data of important national cases should reveal an overall historical pattern. Thus, I extensively explain the justification for country-year selection and coding procedures. It is, of course, essential to remember that my purpose here is to provide a means of relating a country's civilian nuclear development to its proliferation risk, rather than developing an “ideal model.” Technical determinants alone do not provide such conclusive evidence.

The significance of country-year selection becomes evident when analyzing states that developed nuclear weapons after the NPT opened for signature. Detonation of a nuclear test explosion prior to 1 January 1967, was set as the NPT’s benchmark for distinguishing between the permitted NWS and the remaining NNWS (NPT 1968). Still, determining that a state has crossed a line and proliferated is more complicated than observing a nuclear test. There are still questions among scholars about when a state should be considered a “latent nuclear power,” “nuclear-capable,” or a “nuclear-weapon state” (Hymans 2010; Fuhrmann and Tkach 2015). In the NPT environment, some states that acquired nuclear weapons have also never carried out a verified nuclear test. Another difficulty may arise if a country conducted a test but then waited to build an arsenal until a later date. Finally, it is possible to assemble nuclear weapons and then delay a test for political or technical rationales – or have an ally conduct a proxy test. Such considerations reaffirm my commitment to transparent coding and country-year selection. Accordingly, I focus on evidence of nuclear explosive tests having taken place, or in the absence of testing, indications that tests were possible but not conducted due to rationales like political deals with allies (see e.g., Rabinowitz 2014). Minor adjustments to the years analyzed below should generally have only minimal implications for NFC Index scores.

**Group 1: Successful Proliferators**

India, Pakistan, Israel, and North Korea are nuclear-armed states lying outside the NPT and its legal prohibitions and verification activities. As noted above, South Africa successfully developed nuclear weapons before dismantling them and abandoning the military aspects of its fuel cycle. These five states form the first group for which I calculate the NFC Index. Below, I explain rationales for country-year selection, including India (1974, 1998), Pakistan (1990, 1998), Israel (1979), South Africa (1982), and North Korea (2006).

India conducted its first test in 1974, dubbed the “Smiling Buddha” peaceful nuclear explosion (PNE). Following China’s first test in 1964, India was arguably just 6–18 months from having the technical capability to follow suit after a political order (Sagan 1996–1997). There is some debate over whether domestic political factors (Perkovich 1999) or security concerns (Debs and Monteiro 2017) motivated Prime Minister Indira Gandhi’s 1972 decision to accept the recommendation of pro-bomb scientists to test. Regardless of whether Gandhi’s primary driver was to bolster falling support for her political party, or if it stemmed from India’s inability to obtain US security assurances (recalling the 1962 Sino–India War), the PNE shocked the world. But
despite Smiling Buddha, New Delhi did not declare its nuclear weapon status until May 1998, when it openly conducted four more tests for military purposes (Ganguly 1999). I therefore calculate the NFC Index to account for nuclear fuel cycle infrastructure in both 1974 and 1998.

Pakistan’s path to nuclearization began after the country’s defeat in the 1971 Indo-Pakistani War. According to Narang (2014, 56), the objective of the program was “to avoid another massive conventional defeat at the hands of the Indians.” Washington had not intervened to prevent Islamabad’s defeat in the war, and that same year, India signed a Treaty of Peace, Friendship, and Cooperation with the Soviet Union (Debs and Monteiro 2017). Perceiving dire security threats, in January 1972, Prime Minister Zulfi kar Ali Bhutto ordered Pakistani scientists to develop a nuclear weapon within three years (Khan 2012; Rabinowitz 2014). While there are unconfirmed reports that Pakistan had the technical wherewithal to assemble a nuclear device as early as 1987 (Hagerty 1998), its first nuclear tests were not conducted until two weeks after the May 1998 tests by India (Ahmed 1999). US military aid authorization may offer a clearer marker of Pakistan’s nuclear status, as Congress conditioned aid on presidential certification – based on intelligence – that Pakistan did not possess nuclear weapons. In 1990, President George H. W. Bush did not certify Pakistan’s non-nuclear status for the first time, although there are reasons to believe non-certification might have been appropriate a year earlier (Debs and Monteiro 2017). There has also been speculation that China carried out a proxy test of the first Pakistani bomb in May 1990 (Reed and Stillman 2009). Given the 1990 events and declared 1998 tests, I calculate Pakistan’s NFC Index for both years.

Israel is a special case because it is suspected to possess nuclear weapons (Kristensen and Norris 2017) but has never openly declared its nuclear status. On the contrary, strategic ambiguity outside of the NPT is a centerpiece of Israeli security policy. Prominent historical accounts of the covert Israeli nuclear program allege that the country may have possessed an assembled weapon as early as the Six-Day War in 1967 (Cohen 1998; Karpin 2006). Aside from these reports, the subject of a possible Israeli test remains controversial. On one hand, Israel may have opted against an overt test to avoid embarrassing the United States, its main ally (Rabinowitz 2014). But on the other hand, the US Vela 6911 nuclear explosion monitoring satellite detected a double-optical flash over the Southern Indian Ocean in 1979. A US government commission assessed inconclusive proof of an Israeli test, but nuclear explosion monitoring experts from the Los Alamos National Laboratory believed otherwise (Richelson 2007). The 1986 Israeli nuclear disclosures to the British press by technician Mordechai Vanunu also indicated the development of miniaturized boosted fission weapons that would require explosive testing (Weiss 2015). Recently, scientists have offered new assessments of the satellite evidence, alongside radionuclide and hydroacoustic data, supporting the conclusion that a nuclear explosion did indeed take place in 1979 (De Geer and Wright 2018). Due to the body of highly suggestive evidence, I offer the NFC Index assessment of Israeli nuclear capabilities in 1979.

South Africa is another country that produced nuclear weapons outside the NPT, but Pretoria is the only state to voluntarily dismantle its arsenal. In the 1970s, Apartheid South Africa began pursuing nuclear weapons because it confronted a growing communist presence in its region and had little US support (Debs and
Monteiro 2017). The South African government built a test site in the Kalahari Desert in 1977 and may have assembled its first gun-type device that year, but it lacked fissile material for a weapon (Purkitt and Burgess 2005). Observers have also speculated as to whether the 1979 Vela incident was actually a South African test, possibly conducted in collaboration with Israel (Harris et al 2004), but Pretoria had a limited amount of HEU at the time and “was also not known to have a developed an implosion-type design requiring testing at that stage” (Heinonen 2016, 153). Reportedly, South Africa assembled its first working gun-type nuclear device with weapons-grade HEU in 1979 and a second one in 1982; it could indeed have tested if a decision had been made (Reiss 1995). A test was, in fact, considered in 1988 but prevented by US intervention (Rabinowitz 2014). Only after making plans to dismantle its arsenal of six air-deliverable weapons did South Africa accede to the NPT in 1991, with the end of the segregationist Apartheid Era subsequently arriving in 1994. Short of an actual test, it is challenging to select a date for calculating the NFC Index. I select 1982 because Pretoria had two assembled nuclear devices, ongoing HEU production, and a test site that would have allowed for a nuclear detonation at that time.

North Korea is the most recent addition to the nuclear weapons club. Its nuclear program dates to 1965, when Pyongyang began operating a research reactor at Yongbyon procured from the Soviet Union after numerous requests (Ku 2017). Throughout the 1980s, the Soviet Union pressed the DPRK to accede to the NPT – committing to the non-nuclear norm – so it could sell a nuclear power reactor to Pyongyang. But after acceding to the NPT in 1985, North Korea stalled the signing of its safeguards agreement with the IAEA, and later anomalies caused the Agency to request a special inspection (Radchenko 2015). In response, North Korea announced its withdrawal from the NPT, but the 1994 Agreed Framework with the United States averted it (Martin 2002). At the time, US intelligence agencies were convinced that Pyongyang had plutonium stocks to produce a few bombs, consistent with Sagan’s (2010) historical observation that dictatorships are more likely than democracies to cheat after joining the NPT. The eventual collapse of the Agreed Framework saw North Korea finalize its NPT withdrawal in 2003 and conduct its first nuclear test in 2006, with five more to follow by 2017. Today, the regime appears “confident in existential deterrence and [its] ability to deliver nuclear warheads mounted on ballistic missiles” (Herzog 2018a). DPRK pursuit of nuclear weapons under the guise of peaceful uses epitomizes the linkage between military and civilian nuclear technologies. I analyze the NFC Index for 2006, the year of the first DPRK test.

**Group 2: Failed and Suspected Proliferators**

The second group includes those countries that signed the NPT, but nevertheless pursued nuclear weapons capabilities or were subject to international suspicion for doing so behind a façade of peaceful uses. I include assessments of the NFC Index of four countries

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5Regardless, North Korea is the only state to successfully develop nuclear weapons after joining the NPT. And the fact that Pyongyang only confirmed such capabilities with a test after its withdrawal from the NPT serves to highlight the normative power of the Treaty. On the normative power of the NPT, see Rublee (2009) and Budjeryn (2015, 2016).
at critical junctures for their nuclear fuel cycles: Iraq (1991), Syria (2007), Libya (2003), and Iran (2019). Similar to North Korea, potential wrongdoing by these states is consistent with Sagan’s (2010) point about NPT compliance and political regime type⁶.

Iraq and Syria are similar cases, as their nuclear ambitions were thwarted by external military action. Security challenges from Iran and Israel are believed to have motivated Iraq, while threats from Israel and the United States are thought to have driven Syria. While Israel destroyed an early Iraqi nuclear reactor at Osirak in 1981 (Braut-Hegghammer 2011; Kreps and Fuhrmann 2011), Iraq reconstituted its program primarily through attempts at uranium enrichment (Brands and Palkki 2011; Hymans 2012; Braut-Hegghammer 2016). However, the 1990–1991 Gulf War effectively halted progress toward the bomb; Baghdad’s nuclear infrastructure was dismantled under United Nations and IAEA oversight. Allegations of new nuclear weapons development made by the George W. Bush administration before the 2003 US invasion of Iraq have not been substantiated. Syria explored the plutonium route by attempting to build a nuclear reactor at al-Kibar, possibly with DPRK technical assistance. An Israel airstrike in 2007 destroyed the construction site (Spector and Cohen 2008; Kreps and Fuhrmann 2011). Since then, Syria has been on the agenda of the IAEA Board of Governors. I look at the NFC Index in the year of program termination – 1991 for Iraq and 2007 for Syria, respectively – to determine where they stood relative to successful proliferators.

Libya pursued a nuclear weapons program through both the uranium and plutonium routes, involving considerable foreign assistance. During the 1980s, Libyan leader Colonel Moammar Gaddafi obtained technologies from proliferation black markets to build nuclear weapons to counter the suspected Israeli arsenal. In the end, Tripoli advanced mostly along the uranium path because of gas centrifuge equipment and technical expertise supplied by the father of the Pakistani nuclear bomb, A. Q. Khan, and his proliferation network (Albright and Hinderstein 2005; Hymans 2012; Braut-Hegghammer 2016). To improve relations with Britain and the United States after the seizure of several shipments of proliferation-sensitive cargo, Gaddafi agreed to dismantle his nuclear program in December 2003 (Litwak 2007). Dismantlement gave rise to the controversial “Libya Model” of counterproliferation, “wherein US technical experts collected [Libya’s] nuclear program and transported the components to Oak Ridge National Laboratory in Tennessee” (Herzog 2018b, 7). Like for Iraq and Syria, I use discontinuation of the Libyan nuclear program (2003) for NFC Index calculations.

The jury is still out on whether Iran will eventually acquire nuclear weapons, as it used to have an active military program in parallel with civilian nuclear energy development. Iran’s nuclear program began in the 1950s under Reza Shah Pahlavi, moving at a slow pace until Tehran received a US research reactor and technical assistance during the 1960s and the 1970s through the Atoms for Peace Program (Tabatabai and Esfandiary 2018). Iran pursued a series of nuclear activities that were not declared to the IAEA during the 1990s and 2000s. However, a 2007 US National Intelligence Estimate concluded with “high confidence” that the Islamic Republic had suspended nuclear weapons-related research in 2003 (Litwak 2008). The 2015 JCPOA placed limits on Iranian nuclear

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⁶Along these lines, Miller and Sagan (2009) have suggested that proliferation challenges may be exacerbated in the future since the next generation of civilian nuclear powers on the horizon appears decidedly less democratic than its predecessors.
capabilities – alongside intrusive IAEA verification – without dismantling them (Mousavian and Mousavian 2018). Yet, US withdrawal threatens the collapse of the deal and Tehran’s provocative return to uranium enrichment without restrictions. The Nuclear Threat Initiative (2019) notes that Iran now possesses a complete uranium fuel cycle capability. Accordingly, I measure the Iranian NFC Index for 2019.

**Group 3: Norm Embracers**

The final group of states embraced the non-nuclear norm of the NPT. Some of these states joined the Treaty shortly after it opened for signature in 1968, while others held out for decades. This group is comprised of three types of states. First, Japan and South Korea were early NPT signatories that possessed civilian nuclear technologies. Second, Argentina and Brazil only acceded to the Treaty after considerable indigenous fuel cycle development. Third, Saudi Arabia has not been suspected of violating the NPT, but its leaders’ rhetoric and interest in uranium enrichment have raised eyebrows. Analysis of NFC Index scores in this group enables observation of capability levels when these states accepted the NPT as well as their current fuel cycle status as NNWS. I examine the following data: Japan (1970, 2019), South Korea (1968, 2019), Brazil (1998, 2019), Argentina (1995, 2019), and Saudi Arabia (1988, 2019).

Japan and South Korea had civilian nuclear technologies when they signed the NPT. Although viewed as potential proliferators at the time, they are now well-established NNWS. In the 1940s, the Japanese military had a nuclear weapons program, which was abandoned by the end of the Second World War (Solingen 2007). Prior to Japan signing the NPT in 1970, a “secret, nongovernmental study” concluded that Tokyo should remain non-nuclear (Campbell and Sunohara 2004, 223). As a new democracy, Japan founded the Japan Atomic Energy Commission in 1956 (Takubo 2008) and has since developed a comprehensive nuclear energy program with ENR capabilities. Despite powerful nonproliferation norms in Japan due to the Hiroshima and Nagasaki legacy (Rublee 2009), Tokyo’s advanced nuclear energy program has raised concerns about proliferation if leaders grow to doubt extended deterrence and security assurances from the Trump administration vis-à-vis China and North Korea (Debs and Monteiro 2018). South Korea received its first research reactor from the United States in 1962 and began building a power plant in 1970 (Hersman and Peters 2006). Seoul had a covert military program in the 1970s, despite signing the NPT in 1968, but quickly abandoned it under US pressure and ratified the Treaty in 1975 (Reiss 1988). Today, some observers fear that weak US assurances might drive South Korea to proliferate in the face of an aggressive North Korea (Debs and Monteiro 2018). Recent survey-based studies have even shown that more than half of the South Korean population supports nuclearization (Ko 2019; Sukin, forthcoming).

Argentina and Brazil both resisted the NPT at its introduction because of structural inequalities entailed in allowing five states to be NWS, alongside their mild dyadic rivalry. The Argentine government first decided to acquire a German reactor using natural uranium fuel in 1968 (Hymans 2001) and procured a Canadian reactor powered by natural uranium and heavy water thereafter (Goldemberg, Alvim, and Mafra 2018). Over several decades, Argentina constructed unsafeguarded ENR facilities and planned indigenously designed reactors (Hymans 2012). Brazilian interest in nuclear energy dates to
the early 1950s, when Admiral Álvaro Alberto obtained ultracentrifuges from occupied West Germany (Goldemberg, Alvim, and Mafra 2018). The country received its first US research reactor in 1956 under the Atoms for Peace Program and purchased a power reactor from Westinghouse in the late 1960s. Brasília eventually developed civilian capabilities for both spent-fuel reprocessing and uranium enrichment (Spektor 2016; Dalaqua 2019). Brazil also had a parallel military nuclear program that never made significant progress (Spektor 2016). The two South American rival states eventually engaged in bilateral transparency and confidence-building measures to show each other and the world they were not seeking the bomb. In 1991, they established the Argentine–Brazilian Agency for Accounting and Control of Nuclear Materials (ABACC), which verifies the peaceful nature of their nuclear programs (Nascimento Plum and Resende 2016). By the time Argentina (1995) and Brazil (1998) joined the NPT, they had nuclear energy programs that could support weapons-grade fissile material production.7

Unlike the other countries in this group, Saudi Arabia has never had any fuel cycle capabilities, not even a single nuclear reactor (although its first research reactor is under construction at the King Abdulaziz City for Science and Technology). Before Riyadh acceded to the NPT in 1988, the Kingdom resisted the Treaty due to Israel’s refusal to join. However, historical evidence strongly suggests that Saudi actions were more political posturing than actual interest in nuclear weapons (Lippman 2004). Crown Prince Mohammed bin Salman’s stated intention to develop nuclear weapons if Iran does so, combined with difficulties over the JCPOA and Saudi interest in civilian nuclear technology (Miller and Volpe 2018; Sokolski and Tobey 2018), are a potential cause for concern. Riyadh claims to seek nuclear energy to secure long-term economic needs after the eventual decline of fossil fuels. But like its rival Iran, whether Saudi Arabia develops the bomb remains to be seen.

**The Nuclear Fuel Cycle Index**

*Focus on the Fuel Cycle*

To explore the relationship between state decisions to proliferate and levels of civilian fuel cycle infrastructure, I quantify the latter using the NFC Index. The nuclear fuel cycle comprises various activities necessary to modify nuclear materials (uranium) into a form suitable for sustaining a chain reaction in a power or research reactor. The stated civilian goal is electricity generation or other applications like medical isotope production. “front-end” fuel cycle activities refer to stages of the process that take place before the introduction of uranium fuel into the reactor. These stages include uranium mining, milling, conversion, enrichment (if necessary), and fuel fabrication. Furthermore, depending on the desired level of uranium enrichment and the type of reactor, sustaining a nuclear chain reaction may require the use of heavy water as a moderator. “Back-end” fuel cycle activities are stages of the process involving irradiated uranium fuel after

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7Brazil has been working on the development of the Álvaro Alberto nuclear-powered attack submarine project since the 1970s. While this has caused some observers to express fears of proliferation, the Brazilian government and navy have been clear that the submarine and its associated facilities will fall under new bilateral ABACC and international IAEA safeguards (Almeida Silva and Moura 2016; see also Goldemberg, Alvim, and Mafra 2018).
removal from the reactor. After about three years, uranium fuel in a power reactor has become “spent” and will require removal of the fuel rods and refueling.

Each of the different stages of the fuel cycle may be necessary for a successful civilian nuclear energy program. That said, these same technologies can be used for the production of nuclear weapons while there are no international restrictions on their civilian development per NPT Article IV. ENR technologies are the most sensitive fuel cycle elements because they are the gatekeepers to the two known pathways to building the bomb. Enriching uranium by 3–5% can fuel nuclear reactors, but if refined to a much higher level (preferably above 90%), uranium can serve as fissile material for nuclear weapons. Similarly, plutonium extracted from spent fuel or irradiated uranium targets could be used to create a bomb.

**NFC Coding Rules**

To quantify the nuclear infrastructure of a given country, I identify each fuel cycle stage and highlight its contribution to the NFC Index. The Index consists of two groups of technologies containing a total of eight elements and offers a more in-depth exploration of the fuel cycle than previous social science studies. Quantification of these elements allows an assessment of the quality and quantity of a state’s nuclear fuel cycle and energy program facilities. This analysis offers comparative historical insights into whether or not a state’s civilian nuclear program could likely support nuclear weapon development.

The IAEA and other international organizations like INTERPOL monitor nuclear smuggling, particularly across the former Soviet Republics, with incidents overwhelmingly involving gram-level quantities of fissile materials (IAEA 2020b). This highlights the great difficulty of trying to build the bomb on the basis of illicit material trafficking without having national ENR capabilities. Even the A. Q. Khan nuclear smuggling network provided would-be proliferators with technologies and blueprints for fissile material production and nuclear weapon design, rather than the materials themselves (Albright and Hinderstein 2005). Since my objective is to assess relative proliferation risk based on a state’s civilian nuclear infrastructure, the NFC Index does not account for these types of illicit fissile material smuggling transactions.

To start, the NFC Index draws on the IAEA Department of Safeguards’ Physical Model, shown in Figure 1, to identify and measure a country’s level of development regarding the key fuel cycle technologies for acquiring a nuclear weapon. The first group of technologies follows the flow of nuclear materials throughout the fuel cycle and consists of six individual elements:

1. Uranium mining and milling
2. Uranium conversion
3. Uranium enrichment
4. Fuel fabrication
5. Heavy water production
6. Reprocessing

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8Black market nuclear technology transfers are far more common and present a serious proliferation challenge (Bunn et al. 2018).
I score a state’s nuclear fuel cycle on a 10-point scale for each of these categories to assess its overall level of development based upon the IAEA (2009, 5) scale of operation guidelines. If a country has several facilities consisting of the same scale or different scales, I assign a score based upon its highest-level facility with the longest operating experience. After a decade, a country can no longer gain further points for this facility due to predicted technology maturation and operational experience acquisition. This also avoids overweighting very old facilities such as those with origins dating to the early stages of the Atoms for Peace Program. As noted above, the NFC Index only accounts for domestic capabilities and does not include possible foreign transfers of uranium material or heavy water. Foreign assistance in building facilities and transferring fuel cycle technologies are, of course, represented in the NFC Index output since it includes all national facilities. This is an essential component of the NFC Index; in the NPT era, no country has developed a wholly indigenous civilian nuclear program.

Below are the metrics employed to score national capabilities dealing with these six fuel cycle technologies:

- **0 points**: No such element is present in the country’s nuclear program.
- **1 point**: The country has explored this option and conducted relevant research and development activities. Or, the construction of a facility is underway in a given year.
- **2 points**: The process is taking place or being studied in a laboratory-scale facility. For every five years of operating a facility, the country can gain an additional point. For example, five years of operations will yield 3 points while ten years will score 4 points. Operation beyond ten years will still account for 4 points.
- **5 points**: The process is taking place in a pilot-scale facility prior to the establishment of commercial or industrial facilities. For every five years of operating a facility, the country can gain an additional point. For example, five years of
operations will yield **6 points** while ten years will score **7 points**. Operation beyond ten years will still account for **7 points**.

- **8 points**: The process is taking place in a commercial- or industrial-scale facility. For every five years of operating a facility, the country can gain an additional point. For example, five years of operations will yield **9 points** while ten years will score **10 points**. Operation beyond ten years will still account for **10 points**.

The second group of technologies assesses the quality and quantity of a state’s civilian nuclear energy program. Two technologies are included:

1. Research reactors
2. Power reactors

I assign a score of **0 points** if no such reactors are present on the country’s territory. Score levels of **1 point through 10 points** indicate the respective quantity of reactors in a country (e.g., **6 points** equals six reactors, whereas **10 points** represent ten or more reactors). The final score also takes into account national operating experience, as every three years of successful operation increases the score by an additional point. For example, if a country operated one reactor for six years before the year for which I calculate the NFC Index, it scores **3 points**. This gradual score increase accounts for additional plutonium that could be extracted from spent fuel or irradiated uranium targets.

Finally, each element of the nuclear fuel cycle makes a heterogenous contribution to potential nuclear weapons development. As noted above, ENR elements represent two direct routes to weapons production and account for a weighted total of up to **2 points** each in a country’s aggregated 10-point NFC Index. The remaining six elements may contribute up to **1 point** each. The sum of these elements represents a state’s NFC Index in a given year. Thus, the NFC Index may be **0 to 10 total points**. A total of **0 points** indicates a state has no indigenous nuclear fuel cycle and cannot produce nuclear weapons. A total of **10 points** represents a fully developed nuclear fuel cycle that could support weapons-grade material production without difficulty (subject to a political order).

It should be noted that an NFC Index for a nuclear-capable state could be quite low, hypothetically, if it chose to eschew most fuel cycle elements and only invest in pilot-scale uranium enrichment or plutonium separation technologies for weapons production. However, today’s potential proliferators must develop nuclear weapons under the cover of a peaceful nuclear program due to the NPT and rigorous IAEA safeguards. This means that they will also have to invest in other elements of the fuel cycle at a commercially- or industrially-viable scale if they wish to avoid pronounced international scrutiny. In this sense, the danger zone can sometimes be a potential marker of a country’s intention to develop nuclear weapons, as a middling level of fuel cycle development would not serve

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9I am also grateful to an anonymous reviewer for noting that it is theoretically possible for a country to have a high NFC Index by developing commercial- or industrial-scale facilities in all fuel cycle processes except for ENR. This would be an exceptionally rare situation, however, as only Canada has a large fleet of natural uranium-fueled reactors (IAEA 2020c). A hypothetical country that chose to pursue this unlikely route would attract a great deal of suspicion from the international community. For this specific reason, Iran’s IR40 heavy water-moderated reactor at Arak was converted to use enriched uranium as part of the Iran Nuclear Deal. This pathway would not be an optimal route for pursuing a covert nuclear weapons program in the NPT era.
viable electricity generation objectives. This is why it is critical to pay careful attention to states whose level of nuclear development falls in the danger zone. Additionally, engaging in indigenous ENR activities requires some level of investment in other “front-end elements” of the fuel cycle to obtain uranium or plutonium in the first place. While the five NPT-designated NWS are different from other potential proliferators – due to their pursuit of military nuclear activities in the pre-NPT era – and classified data availability complicates NFC Index calculations, my initial assessment indicates that they were also in the danger zone at the time of their first tests.

I compiled data using a variety of sources. First, I used the IAEA (2020a) Integrated Nuclear Fuel Cycle Information System (iNFCIS), a database of global “front- and back-end fuel cycle facilities” and their operational status. States also report planned facilities to the IAEA. The iNFCIS covers all stages of the nuclear fuel cycle, from uranium ore production to spent-fuel storage. I also drew on the World Nuclear Industry Handbook (Nuclear Engineering International 2019), an annual list of research, power, and test reactors as well as fuel cycle facilities. Finally, I examined documentation of operating and forthcoming experimental facilities from the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (2019). Compiled country profiles by research institutes like the Carnegie Endowment for International Peace, the Federation of American Scientists, and the Nuclear Threat Initiative helped supplement and cross-validate data or reconstruct information about covert historical facilities in some cases.10

In sum, this methodology is a useful synopsis of a state’s civilian nuclear fuel cycle capabilities in a given year for four reasons. First, the NFC Index draws on official IAEA documents for understanding the fuel cycle’s relationship to nuclear weapon acquisition. Second, I calculate scores based on the best publicly-available technical data. Third, the coding upweights the value of more proliferation-sensitive facilities – although use of these technologies also requires the development of other elements of the fuel cycle. And finally, the NFC Index takes into account both qualitative and quantitative considerations such as the scale of operations, operating experience, and potential fissile material accumulation associated with civilian nuclear energy programs.

Results and Interpretation

Here, I display the NFC Index for 14 different states at years of critical significance to their nuclear programs as described above in the country snapshots. Table 1 presents the civilian nuclear fuel cycle capabilities of these countries, the contribution of various elements to the NFC Index, and an aggregated national score for each country-year.

The data in Table 1 highlight historical civilian nuclear fuel cycle capabilities of successful proliferators (Group 1), failed and suspected proliferators (Group 2), and states that embraced the nonproliferation norm (Group 3). The lowest recorded NFC

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10 While great care was taken in coding, new disclosure of covert facilities or historical data may alter scores. Such disclosures, disagreement over facility characterization, or slight adjustments to years in the data-points should minimally affect the heuristic utility of NFC Index scores. The NFC Index is based on open sources rather than classified intelligence, but it is useful to mention that proliferators in the NPT era have supplemented civilian nuclear programs with a few covert facilities. Put simply, the entirety of the fuel cycle cannot be hidden from the watchful eyes of the IAEA, national intelligence agencies, societal verification, and the broader international community.
Index I observe for a nuclear test-capable state is 4.4 points for South Africa (1982), and at 5.5 points, the DPRK (2006) has the lowest score for a confirmed test. Israel’s (1979) score is 5.7 points when the Vela incident took place. The highest value for a nuclear test is India (1998), which has a score of 9.4 points when New Delhi tested and did not declare it a PNE. Yet, India (1974) had already demonstrated its nuclear capability with the Smiling Buddha PNE, scoring 6.5 points. This means that the highest threshold for a first test is represented by Pakistan (1998) at 7.8 points. Pakistan’s (1998) NFC Index is also deceptive, however, as Pakistan (1990) has an NFC Index of 6.5 points when George H. W. Bush became the first sitting US President not to certify its non-nuclear status based on intelligence assessments. Interestingly, both India and Pakistan score lower at their first test-capable years than Argentina (7.2) and Brazil (6.6) when they acceded to the NPT in 1995 and 1998, respectively. Libya (2.4) and Syria (0.8) were somewhat distant from the minimum comparative historical threshold for developing the bomb. Iraq (3.4) was much closer and likely just a few years away from having the fuel cycle capabilities needed to support indigenous production of nuclear weapons.

Figure 2 plots the data-points from Table 1 and illustrates historical levels of technological sophistication associated with nuclear weapons proliferation (binary outcome). Red dots represent country-year data from Group 1 states, which succeeded in developing the bomb. Yellow dots represent Group 2 states, which were determined to have carried out activities in violation of the NPT or were suspected by the international community of such legal transgressions. Green dots represent Group 3, which embraced the nonproliferation norm. The stepwise curve represents theorized risk of nuclear
proliferation, illustrating the use of this heuristic tool rather than providing an exact measurement – given the importance of political dynamics.

The analysis shows a few distinct historical trends. At medium levels of nuclear fuel cycle capability, states are at the greatest risk for horizontal proliferation, so I label this general area as the theorized danger zone. Among the country-years I analyzed, NFC Index scores between 4.4 and 6.5 were the most likely range for weapons development. The high Indian and Pakistani scores in 1998 obscure the fact that these states were already nuclear-capable at the time of their first declared military nuclear tests.

At low levels of nuclear fuel cycle development, states have historically been unable (technologically incapable) to develop nuclear weapons even if actively pursuing them. Many states such as Japan and South Korea also signed onto the NPT at low levels of fuel cycle capability prior to embarking on more ambitious nuclear energy plans. And at high levels of nuclear fuel cycle development, states that have not proliferated are unlikely to reverse course and build the bomb. This finding should be robust, conditional upon the continuation of a strong nonproliferation norm and absent dramatic changes in states’

Figure 2. Historical cases of nuclear proliferation, forbearance, and rollback with theorized proliferation risk assessment.

*India (1998) and Pakistan (1998) developed military nuclear capabilities several years before these tests.
security environments, such as losing the protection of a nuclear-armed patron state. If such changes were to occur, it remains unclear if the deterrent or compellent value of a latent “virtual arsenal” in the form of threshold state status would be sufficient to encourage nuclear forbearance.

Recalling the country snapshots, it is also interesting to note that countries which achieved that minimum NFC Index for successful proliferation possessed amounts of fissionable material required to produce multiple nuclear devices. Perhaps this should not be surprising, as nuclear explosive testing allows a state to gather important scientific data to improve its arsenal, hence the multitude of diagnostic cables used in underground testing. If a state uses all of its fissile materials in a test, there will be none left for the construction of an improved device. The North Korean case exemplifies this trend, as the DPRK may have had fissile materials to build a bomb in the early 1990s. Only after the regime produced a considerably larger stockpile of fissile materials – enough for several devices – did Pyongyang conduct its first test in 2006.

**Conclusion and Policy Implications**

Sometimes the best ways to describe findings in one field are to draw analogies with another. In many respects, my NFC Index analysis of proliferation has similarities with incidents of violent crime. Very young children are unlikely to be capable of committing violent offenses, just as states with low levels of civilian fuel cycle development are unlikely to be capable of nuclear proliferation. Elderly people who have never committed a violent crime are unlikely to do so in their later years, just as states that successfully master sophisticated fuel cycle technologies without proliferating are unlikely to take a sudden U-turn to make a drive for the bomb. Fortunately, the percentage of states in the world that are in the proliferation danger zone is quite small.

Still, states seeking to develop nuclear weapons under the guise of peaceful uses of nuclear energy have incentives to misrepresent their intentions. The danger zone is also perhaps a signaling zone where states reveal their “type” (Glaser 2010) – proliferator or not – to the international community. After all, a state with an interest in building the bomb is unlikely to wait until the realization of a full-scope civilian nuclear program to do so. States that master the fuel cycle and exit the danger zone in forbearance are, likewise, signaling their type as being comparatively unwilling to proliferate.

Three conclusions follow from the historical record. First, it is important to avoid exaggerating the proliferation risks from states that have not entered the danger zone. Second, intelligence agencies, scholars, analysts, and other interested observers should very closely watch the activities of states that are in the danger zone. Third, there are generally reasons to trust the nonproliferation bona fides of states that master the fuel cycle and exit the danger zone. Regardless, states should always be vigilant and apply Nuclear Suppliers Group (NSG) standards on cross-border transactions and insist on full application of IAEA safeguards to the fuel cycle.

These findings have implications for proliferation concerns in East Asia. Japan and South Korea signed the NPT when they had relatively low levels of civilian fuel cycle technologies. While their journeys to become established NNWS and advocates of the nonproliferation norm faced some setbacks along the way, each has now engaged in significant peaceful nuclear developments. Reversing course and developing nuclear
weapons would entail severe consequences for their nuclear energy programs, among other punishments. India’s NSG waiver also supports the notion that no single country can sustain a prospering nuclear energy program in isolation (Perkovich 2010). The required inputs to succeed as a civilian nuclear power simply necessitate access to the global supply chain. Further, Tokyo – and to a lesser extent, Seoul – may already have the ability to deter and compel other states through the strategic use of nuclear latency. Although these East Asian states approached the NPT in a dramatically different fashion than Argentina and Brazil, there are clear parallels. Higher levels of civilian nuclear development, absent proliferation, have historically correlated with a low likelihood of future proliferation aspirations. Regardless, it is important to note that South Korea remains in the danger zone, adding increased urgency to resolving the North Korean nuclear crisis. It may seem counterintuitive and controversial to suggest that the development of more expansive ENR capabilities by South Korea would make the country less of a proliferation risk. Yet, commercial- and industrial-scale facilities of this nature – as opposed to overt or covert laboratory or pilot facilities – would help to further solidify Seoul’s dependence on international nuclear markets and bolster its ability to achieve latent nuclear deterrence.

Analysis of the NFC Index also may illuminate policy prescriptions for addressing horizontal proliferation risks in the Middle East. Saudi Arabia, like Japan and South Korea, is currently an NNWS in good standing under the NPT. However, Riyadh’s rhetoric about potentially discarding the Treaty in favor of proliferation offers potentially alarming context alongside research reactor construction and Section 123 negotiations with the United States – including an apparent unwillingness to forgo uranium enrichment. Still, the Kingdom has no fuel cycle capabilities at present, so it will be years until it could develop a nuclear breakout capacity. It will be imperative for observers to rigorously scrutinize Saudi activities if the Kingdom approaches the danger zone. Iran is an NNWS that has relatively developed civilian nuclear capabilities, including a complete uranium fuel cycle. But unlike Saudi Arabia, Iran is in the proliferation danger zone and just on the cusp of mastering fuel cycle technologies. The development of a more sophisticated fuel cycle will not, in itself, remove Iran’s security threats and some other potential drivers of proliferation. Yet, since the Islamic Republic has made clear its intention to harness the power of civilian nuclear energy, perhaps it is in the international community’s interest to help shepherd Tehran through the danger zone. Though clearly a controversial suggestion, the achievement of these ends would help Iran move toward technology levels that – for any number of theoretical reasons discussed above – are historically associated with nuclear forbearance. That said, all nuclear cooperation should only take place under strict IAEA safeguards, including Iran’s Additional Protocol, and the monitoring and limitations of the JCPOA.

The analyses stemming from the NFC Index present interesting historical patterns related to nuclear proliferation and peaceful uses of nuclear technologies. Of course, I still

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11It is also important to note differential public opinion on nuclear proliferation in Japan and South Korea. While research shows that a majority of South Koreans support the idea of their country developing nuclear weapons (Ko 2019; Sukin, forthcoming), this is not the case in Japan. Polling indicates that 75% of the Japanese public wants the Abe administration to join the Treaty on the Prohibition of Nuclear Weapons (Baron, Gibbons, and Herzog 2020). A stunning 85% do not support US use of nuclear weapons against North Korea, even if the DPRK launches a nuclear strike on Japan (Allison, Herzog, and Ko 2019).
advise some caution in drawing universal inferences, although my preliminary analysis reveals that such inferences are appropriate across a range of important cases and years. There may well be, unfortunately, successful future proliferation attempts falling below or above the historical thresholds I laid out, but Figure 2 offers bands of activity that should be predictive of proliferation risks at reasonable levels of confidence.

At the end of the day, nuclear proliferation and the decision to build the bomb are political choices supported by technological breakthroughs. And it is the intersection of the technical danger zone and the motivations for proliferation specified in the literature that should be most concerning. Perhaps states with serious security threats, for example, are the most likely candidates to reveal their type as proliferators in the danger zone. Without necessary technical capabilities, however, politics alone will not result in successful proliferation. The NFC Index thereby offers a way to systematically track technological development that avoids alarmist technical assessments and complements political analysis. Overall, scholars and policymakers could better understand the technical side of proliferation by examining historical cases and looking closely at aggregate levels of civilian nuclear fuel cycle development.

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References

Ahmed, S. 1999. “Pakistan’s Nuclear Weapons Program: Turning Points and Nuclear Choices.” International Security 23 (4): 178–204. doi:10.1162/isec.23.4.178.

Albright, D., and C. Hinderstein. 2005. “Unraveling the A. Q. Khan and Future Proliferation Networks.” The Washington Quarterly 28 (2): 109–128. doi:10.1162/0163660053295176.

Allison, D. M., S. Herzog, and J. Ko. 2019. “Under the Umbrella: Nuclear Crises, Extended Deterrence, and Public Opinion.” Paper presented at the International Studies Association Annual Convention, Toronto, Canada.

Almeida Silva, A. R., and J. A. A. Moura. 2016. “The Brazilian Navy’s Nuclear-Powered Submarine Program.” The Nonproliferation Review 23 (5–6): 617–633. doi:10.1080/10736700.2017.1337625.

Baron, J. B., R. D. Gibbons, and S. Herzog. 2020 “Japanese Public Opinion, Political Persuasion, and the Treaty on the Prohibition of Nuclear Weapons.” Working paper. Yale University and Harvard University Project on Managing the Atom.

Baron, J. B., and S. Herzog. Forthcoming. “Public Opinion on Nuclear Energy and Nuclear Weapons: The Attitudinal Nexus in the United States.” Energy Research & Social Science. doi:10.1016/j.erss.2020.101567

Bin Salman, M. 2018. Interview with Norah O’Donnell. 60 Minutes. March 15. https://www.cbsnews.com/news/saudi-crown-prince-mohammed-bin-salman-iran-nuclear-bomb-saudi-arabia/

Bollfrass, A. K. 2017. The Half-Lives of Others: The Democratic Advantage in Nuclear Intelligence Assessment. PhD diss., Princeton University.

Brands, H., and D. Palkki. 2011. “Saddam, Israel, and the Bomb: Nuclear Alarmism Justified?” International Security 36 (1): 133–166. doi:10.1162/ISEC_a_00047.

Braut-Hegghammer, M. 2011. “Revisiting Osirak: Preventive Attacks and Nuclear Proliferation Risks.” International Security 36 (1): 101–132. doi:10.1162/ISEC_a_00046.

Braut-Hegghammer, M. 2016. Unclear Physics: Why Iraq and Libya Failed to Build Nuclear Weapons. Ithaca, NY: Cornell University Press.

Budjeryn, M. 2015. “The Power of the NPT: International Norms and Ukraine’s Nuclear Disarmament.” The Nonproliferation Review 22 (2): 203–237. doi:10.1080/10736700.2015.1119968.

Budjeryn, M. 2016. The Power of the NPT: International Norms and Nuclear Disarmament of Belarus, Kazakhstan and Ukraine, 1990–1994. PhD diss., Central European University.

Bunn, M., M. B. Malin, W. C. Potter, and L. S. Spector, eds. 2018. Preventing Black Market Trade in Nuclear Technology. Cambridge: Cambridge University Press.

Campbell, K. M., and T. Sunohara. 2004. “Japan: Thinking the Unthinkable.” In The Nuclear Tipping Point: Why States Reconsider Their Nuclear Choices, edited by K. M. Campbell, R. J. Einhorn, and M. Reiss, 218–253. Washington, DC: Brookings Institution Press.

Carnegie, A., and A. Carson. 2019. “The Disclosure Dilemma: Nuclear Intelligence and International Organizations.” American Journal of Political Science 63 (2): 269–285. doi:10.1111/ajps.12426.
Choi, J. 2018. “How to Stop North Korea’s Nuclear Ambition: Failed Diplomacy and Future Options.” Journal of Contemporary East Asia Studies 7 (1): 1–15. doi:10.1080/24761028.2018.1499426.

Cohen, A. 1998. Israel and the Bomb. New York: Columbia University Press.

Dalaqua, R. H. 2019. “‘We Will Not Make the Bomb because We Do Not Want to Make the Bomb’: Understanding the Technopolitical Regime that Drives the Brazilian Nuclear Program.” The Nonproliferation Review 26 (3–4): 231–249. doi:10.1080/10736700.2019.1630094.

De Geer, L.-E., and C. M. Wright. 2018. “The 22 September 1979 Vela Incident: Radionuclide and Hydroacoustic Evidence for a Nuclear Explosion.” Science & Global Security 26 (1): 20–54. doi:10.1080/08929882.2018.1451050.

Debs, A., and N. P. Monteiro. 2017. Nuclear Politics: The Strategic Causes of Proliferation. Cambridge: Cambridge University Press.

Debs, A., and N. P. Monteiro. 2018. “Cascading Chaos in Nuclear Northeast Asia.” The Washington Quarterly 41 (1): 97–113. doi:10.1080/0163660X.2018.1445902.

Deutch, J. M. 1992. “The New Nuclear Threat.” Foreign Affairs 71 (4): 120–134. doi:10.2307/20045313.

Frankel, B. 1993. “The Brooding Shadow: Systemic Incentives and Nuclear Weapons Proliferation.” Security Studies 2 (3–4): 37–78. doi:10.1093/interred/2.3-4.37.

Fuhrmann, M. 2009. “Taking a Walk on the Supply Side: The Determinants of Civilian Nuclear Cooperation.” Journal of Conflict Resolution 53 (2): 181–208. doi:10.1177/0022002708330288.

Fuhrmann, M. 2012. Atomic Assistance: How “Atoms for Peace” Programs Cause Nuclear Insecurity. Ithaca, NY: Cornell University Press.

Fuhrmann, M. 2017. “The Logic of Latent Nuclear Deterrence.” Paper presented at the Annual Meeting of the American Political Science Association, San Francisco. https://pdfs.semanticscholar.org/da10/92d95dbd16a89cee3ad482755698e6424e6.pdf

Fuhrmann, M., and B. Tkach. 2015. “Almost Nuclear: Introducing the Nuclear Latency Dataset.” Conflict Management and Peace Science 32 (4): 443–461. doi:10.1177/0738894214559672.

Fuhrmann, M., and Y. Lupu. 2016. “Do Arms Control Treaties Work? Assessing the Effectiveness of the Nuclear Nonproliferation Treaty.” International Studies Quarterly 60 (3): 530–539. doi:10.1093/isq/sqw013.

Ganguly, Š. 1999. “India’s Pathway to Pokhran II: The Prospects and Sources of New Delhi’s Nuclear Weapons Program.” International Security 23 (4): 148–177. doi:10.1162/isec.23.4.148.

Gheorghe, E. 2019. “Proliferation and the Logic of the Nuclear Market.” International Security 43 (4): 88–127. doi:10.1162/isec_a_00344.

Gibbons, R. D. 2020. “Supply to Deny: The Benefits of Nuclear Assistance for Nuclear Nonproliferation.” Journal of Global Security Studies 5 (2): 282–298. doi:10.1093/jogss/oqz059.

Glaser, C. L. 2010. Rational Theory of International Politics: The Logic of Competition and Cooperation. Princeton, NJ: Princeton University Press.

Goldemberg, J., C. F. Alvim, and O. Y. Mafra. 2018. “The Denuclearization of Brazil and Argentina.” Journal for Peace and Nuclear Disarmament 1 (2): 383–403. doi:10.1080/25751654.2018.1479129.

Gordon, P. H. 2019. “A Path to War with Iran: How Washington’s Escalation Could Lead to Unintended Catastrophe.” Foreign Affairs, May 20. https://www.foreignaffairs.com/articles/iran/2019-05-20/path-war-iran

Hagerty, D. T. 1998. The Consequences of Nuclear Proliferation: Lessons from South Asia. Cambridge, MA: MIT Press.

Harris, V., S. Hatang, and P. Liberman. 2004. “Unveiling South Africa’s Nuclear Past.” Journal of Southern African Studies 30 (3): 457–476. doi:10.1080/0305707042000254074.

Heinonen, O. 2016. “Lessons Learned from Dismantlement of South Africa’s Biological, Chemical, and Nuclear Weapons Programs.” The Nonproliferation Review 23 (1–2): 147–162. doi:10.1080/10736700.2016.1182685.

Hersman, R. K. C., and R. Peters. 2006. “Nuclear U-Turns: Learning from South Korean and Taiwanese Rollback.” The Nonproliferation Review 13 (3): 539–553. doi:10.1080/10736700601071629.
Herzog, S. 2018a. “A Way Forward with North Korea: The Comprehensive Nuclear-Test-Ban Treaty.” War on the Rocks, June 11. https://warontherocks.com/2018/06/a-way-forward-with-north-korea-the-comprehensive-nuclear-test-ban-treaty/

Herzog, S. 2018b. “After the Summit: A Next Step for the United States and North Korea.” Arms Control Today 48 (6): 6–11. https://www.armscontrol.org/act/2018-07/features/after-summit-next-step-united-states-north-korea

Hoffman, W., and T. A. Volpe. 2018. “Internet of Nuclear Things: Managing the Proliferation Risks of 3-D Printing Technology.” Bulletin of the Atomic Scientists 74 (2): 102–113. doi:10.1080/00963402.2018.1436811.

Hymans, J. E. C. 2001. “Of Gauchos and Gringos: Why Argentina Never Wanted The Bomb, and Why The United States Thought It Did.” Security Studies 10 (3): 153–185. doi:10.1080/09636410108429440.

Hymans, J. E. C. 2006. The Psychology of Nuclear Proliferation: Identity, Emotions and Foreign Policy. Cambridge: Cambridge University Press.

Hymans, J. E. C. 2010. “When Does a State Become a ‘Nuclear Weapon State’? An Exercise in Measurement Validation.” The Nonproliferation Review 17 (1): 161–180. doi:10.1080/10736700903484728.

Hymans, J. E. C. 2012. Achieving Nuclear Ambitions: Scientists, Politicians, and Proliferation. Cambridge: Cambridge University Press.

IAEA (International Atomic Energy Agency). 2002. “IAEA Safeguards Glossary 2001 Edition.” International Nuclear Verification Series, No. 3. Vienna: IAEA. https://www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/PDF/NVS3_scr.pdf

IAEA (International Atomic Energy Agency). 2009. “Nuclear Fuel Cycle Information System: A Directory of Nuclear Fuel Cycle Facilities.” IAEA-TECDOC-1613, April. https://www-pub.iaea.org/MTCD/Publications/PDF/te_1613_web.pdf

IAEA (International Atomic Energy Agency). 2020a. “Integrated Nuclear Fuel Cycle Information System.” https://www.iaea.org/resources/databases/integrated-nuclear-fuel-cycle-information-system-infics

IAEA (International Atomic Energy Agency). 2020b. “Incidents of Nuclear and Other Radioactive Material Out of Regulatory Control.” Factsheet. https://www.iaea.org/sites/default/files/20/02/itdb-factsheet-2020.pdf

IAEA (International Atomic Energy Agency). 2020c. “Power Reactor Information System.” https://pris.iaea.org/PRIS/home.aspx

IAEA (International Atomic Energy Agency). 2020d. Research Reactor Database. https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx?filter=0

Jo, D.-J., and E. Gartzke. 2007. “Determinants of Nuclear Weapons Proliferation.” Journal of Conflict Resolution 51 (1): 167–194. doi:10.1177/0022002706296158.

Karpin, M. 2006. The Bomb in the Basement: How Israel Went Nuclear and What that Means for the World. New York: Simon & Schuster.

Khan, F. 2012. Eating Grass: The Making of the Pakistani Bomb. Stanford, CA: Stanford University Press.

Ko, J. 2019. “Alliance and Public Preference for Nuclear Forbearance: Evidence from South Korea.” Foreign Policy Analysis 15 (4): 509–529. doi:10.1093/fpa/ory014.

Kreps, S. E., and M. Fuhrmann. 2011. “Attacking the Atom: Does Bombing Nuclear Facilities Affect Proliferation?” Journal of Strategic Studies 34 (2): 161–187. doi:10.1080/01402390.2011.559021.

Kristensen, H. M., and R. S. Norris. 2017. “Worldwide Deployments of Nuclear Weapons, 2017.” Bulletin of the Atomic Scientists 73 (5): 289–297. doi:10.1080/00963402.2017.1363995.

Kroenig, M. 2009a. “Exporting the Bomb: Why States Provide Sensitive Nuclear Assistance.” American Political Science Review 103 (1): 113–133. doi:10.1017/S0003055409000107.

Kroenig, M. 2009b. “Importing the Bomb: Sensitive Nuclear Assistance and Nuclear Proliferation.” Journal of Conflict Resolution 53 (2): 161–180. doi:10.1177/0022002708330287.

Kroenig, M. 2010. Exporting the Bomb: Technology Transfer and the Spread of Nuclear Weapons. Ithaca, NY: Cornell University Press.
Kroenig, M., and T. A. Volpe. 2015. “3-D Printing the Bomb? The Nuclear Nonproliferation Challenge.” *The Washington Quarterly* 38 (3): 7–19. doi:10.1080/0163660X.2015.1099022.

Ku, Y. 2017. “Spear Versus Shield? North Korea’s Nuclear Path and Challenges to the NPT System.” In *North Korea and Nuclear Weapons: Entering the New Era of Deterrence*, edited by K. S. Chull and M. Cohen, 179–194. Washington, DC: Georgetown University Press.

Lippman, T. W. 2004. “Saudi Arabia: The Calculations of Uncertainty.” In *The Nuclear Tipping Point: Why States Reconsider Their Nuclear Choices*, edited by K. M. Campbell, R. J. Einhorn, and M. Reiss, 111–144. Washington, DC: Brookings Institution Press.

Litwak, R. S. 2007. *Regime Change: U.S. Strategy through the Prism of 9/11*. Baltimore: Johns Hopkins University Press.

Litwak, R. S. 2008. “Living with Ambiguity: Nuclear Deals with Iran and North Korea.” *Survival* 50 (1): 91–118. doi:10.1080/00396330801899496.

Liu, Z., and S. Morsy. 2007. “Development of the Physical Model.” International Atomic Energy Agency. IAEA-SM-367/13/07. https://www-pub.iaea.org/MTCD/publications/PDF/ss-2001/PDF%20files/Session%2013/Paper%2013-07.pdf

Martin, C. H. 2002. “Rewarding North Korea: Theoretical Perspectives on the 1994 Agreed Framework.” *Journal of Peace Research* 39 (1): 51–68. doi:10.1177/002234302039001003.

Mearsheimer, J. J. 1990. “Back to the Future: Instability in Europe after the Cold War.” *International Security* 15 (1): 5–56. doi:10.2307/2538981.

Mearsheimer, J. J. 1993. “The Case for a Ukrainian Nuclear Deterrent.” *Foreign Affairs* 72 (3): 50–66. doi:10.2307/20045622.

Mehta, R. N., and R. E. Whitlark. 2017. “The Benefits and Burdens of Nuclear Latency.” *International Studies Quarterly* 61 (3): 517–528. doi:10.1093/isq/sqx028.

Meyer, S. M. 1984. *The Dynamics of Nuclear Proliferation*. Chicago: University of Chicago Press.

Miller, N. L. 2017. “Why Nuclear Energy Programs Rarely Lead to Proliferation.” *International Security* 42 (2): 40–77. doi:10.1162/isec_a_00293.

Miller, N. L. 2018. *Stopping the Bomb: The Sources and Effectiveness of US Nonproliferation Policy*. Ithaca, NY: Cornell University Press.

Miller, N. L., and T. A. Volpe. 2018. “Abstinence or Tolerance: Managing Nuclear Ambitions in Saudi Arabia.” *The Washington Quarterly* 41 (2): 27–46. doi:10.1080/0163660X.2018.1484224.

Miller, S. E., and S. D. Sagan. 2009. “Nuclear Power Without Nuclear Proliferation?” *Daedalus* 138 (4): 7–18. doi:10.1162/daed.2009.138.4.7.

Monteiro, N. P., and A. Debs. 2014. “The Strategic Logic of Nuclear Proliferation.” *International Security* 39 (2): 7–51. doi:10.1162/ISEC_a_00177.

Montgomery, A. H. 2013. “Stop Helping Me: When Nuclear Assistance Impedes Nuclear Programs.” In *The Nuclear Renaissance and International Security*, edited by A. M. Stulberg and M. Fuhrmann, 177–202. Stanford, CA: Stanford University Press.

Montgomery, A. H., and S. D. Sagan. 2009. “The Perils of Predicting Proliferation.” *Journal of Conflict Resolution* 53 (2): 302–328. doi:10.1177/0022002708330581.

Mousavian, S. H., and M. Mousavian. 2018. “Building on the Iran Nuclear Deal for International Peace and Security.” *Journal for Peace and Nuclear Disarmament* 1 (1): 169–192. doi:10.1080/25751654.2017.1420373.

Müller, H., and A. Schmidt. 2010. “The Little Known Story of De-Proliferation: Why States Give up Nuclear Weapons Activities.” In *Forecasting Nuclear Proliferation in the 21st Century: The Role of Theory*, edited by W. C. Potter and G. Mukhatzhanova, 124–158. Vol. 1. Stanford, CA: Stanford University Press.

Narang, V. 2014. *Nuclear Strategy in the Modern Era: Regional Powers and International Conflict*. Princeton, NJ: Princeton University Press.

Nascimento Plum, M. O., and C. A. R. Resende. 2016. “The ABACC Experience: Continuity and Credibility in the Nuclear Programs of Brazil and Argentina.” *The Nonproliferation Review* 23 (5–6): 575–593. doi:10.1080/10736700.2017.1339402.

Nuclear Energy Agency. 2019. “Review of Operating and Forthcoming Experimental Facilities Opened to International R&D Co-operation in the Field of Advanced Fuel Cycles.” Organisation for Economic Co-operation and Development. NEA/NSE/R(2018)4, February
26. http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=NEA/NSC/R(2018)4&docLanguage=En
Nuclear Engineering International. 2019. World Nuclear Industry Handbook. Surrey, UK: Business Press International.

Nuclear Threat Initiative. 2019. “Iran.” https://www.nti.org/learn/countries/iran/

Perkovich, G. 1999. India’s Nuclear Bomb: The Impact on Global Proliferation. Berkeley, CA: University of California Press.

Perkovich, G. 2010. “Global Implications of the U.S.-India Deal.” Daedalus 139 (1): 20–31. doi:10.1162/daed.2010.139.1.20.

Purkitt, H. E., and S. F. Burgess. 2005. South Africa’s Weapons of Mass Destruction. Bloomington, IN: Indiana University Press.

Rabinowitz, O. 2014. Bargaining on Nuclear Tests: Washington and Its Cold War Deals. Oxford: Oxford University Press.

Radchenko, S. 2015. “Russia’s Policy in the Run-Up to the First North Korean Nuclear Crisis 1991–1993.” Woodrow Wilson Center. Nuclear Proliferation International History Project Working Paper, No. 4. https://www.wilsoncenter.org/publication/russias-policy-the-run-to-the-first-north-korean-nuclearcrisis-1991-1993

Reed, T. C., and D. B. Stillman. 2009. The Nuclear Express: A Political History of the Bomb and Its Proliferation. Minneapolis, MN: Zenith Press.

Reiss, M. 1988. Without the Bomb: The Politics of Nuclear Nonproliferation. New York: Columbia University Press.

Reiss, M. 1995. Bridled Ambition: Why Countries Constrain Their Nuclear Capabilities. Washington, DC: Woodrow Wilson Center Press.

Richelson, J. 2007. Spying on the Bomb: American Nuclear Intelligence from Nazi Germany to Iran and North Korea. New York: W. W. Norton.

Rublee, M. R. 2009. Nonproliferation Norms: Why States Choose Nuclear Restraint. Athens, GA: University of Georgia Press.

Rublee, M. R. 2015. “Fantasy Counterfactual: A Nuclear-Armed Ukraine.” Survival 57 (2): 145–156. doi:10.1080/00396338.2015.1026091.

Sagan, S. D. 1996–1997. “Why Do States Build Nuclear Weapons? Three Models in Search of a Bomb.” International Security 21 (3): 54–86. doi:10.2307/2539273.

Sagan, S. D. 2010. “Nuclear Power, Nuclear Proliferation and the NPT.” Paper presented at the Annual Meeting of the American Political Science Association, Washington. https://ssrn.com/abstract=1642168

Sagan, S. D. 2011. “The Causes of Nuclear Weapons Proliferation.” Annual Review of Political Science 14 (1): 225–244. doi:10.1146/annurev-polisci-052209-131042.

Singh, S., and C. R. Way. 2004. “The Correlates of Nuclear Proliferation: A Quantitative Test.” Journal of Conflict Resolution 48 (6): 859–885. doi:10.1177/0022002704269655.

Sokolski, H., and W. Tobey. 2018. “A Poorly Negotiated Saudi Nuclear Deal Could Damage Future Regional Relationships.” National Interest. February 5. https://nationalinterest.org/feature/poorly-negotiated-saudi-nuclear-deal-could-damage-future-24367

Solingen, E. 1994. “The Political Economy of Nuclear Restraint.” International Security 19 (2): 126–169. doi:10.2307/2539198.

Solingen, E. 2007. Nuclear Logics: Contrasting Paths in East Asia and the Middle East. Princeton, NJ: Princeton University Press.

Spektor, L. S., and A. Cohen. 2008. “Israel’s Airstrike on Syria’s Reactor: Implications for the Nonproliferation Regime.” Arms Control Today 38 (6): 15–21. https://www.armscontrol.org/act/2008_07-08/SpectorCohen

Spektor, M. 2016. “The Evolution of Brazil’s Nuclear Intentions.” The Nonproliferation Review 23 (5–6): 635–652. doi:10.1080/10736700.2017.1345518.

Stoll, R. J. 1996. “World Production of Latent Nuclear Capacity.” Rice University dataset. http://es.rice.edu/projects/Poli378/Nuclear/Proliferation/proliferation.html
Sukin, L. *Forthcoming*. “Credible Nuclear Security Commitments Can Backfire: Explaining Domestic Support for Nuclear Weapons Acquisition in South Korea.” *Journal of Conflict Resolution*. doi:10.1177/00220027198888689.

Tabatabai, A., and D. Esfandiary. 2018. *Triple-Axis: Iran’s Relations with Russia and China*. London: I. B. Tauris.

Takubo, M. 2008. “Wake Up, Stop Dreaming: Reassessing Japan’s Reprocessing Program.” *The Nonproliferation Review* 15 (1): 71–94. doi:10.1080/10736700701852928.

Treaty on the Non-Proliferation of Nuclear Weapons. 1968. 729 UNTS 161. 7 ILM 809. https://www.un.org/disarmament/wmd/nuclear/npt/text/

Volpe, T. A. 2017. “Atomic Leverage: Compellence with Nuclear Latency.” *Security Studies* 26 (3): 517–544. doi:10.1080/09636412.2017.1306398.

Volpe, T. A. 2019. “Dual-Use Distinguishability: How 3D-Printing Shapes the Security Dilemma for Nuclear Programs.” *Journal of Strategic Studies* 42 (3): 517–544. doi:10.1080/09636412.2019.1627210.

Weiss, L. 2015. “Flash from the Past: Why an Apparent Israeli Nuclear Test in 1979 Matters Today.” *Bulletin of the Atomic Scientists*, September 8. https://thebulletin.org/2015/09/flash-from-the-past-why-an-apparent-israeli-nuclear-test-in-1979-matters-today/

Yanagisawa, K. 2019. “The North Korea–United States Summit and Possibilities for New Security-Oriented Thinking.” *Journal for Peace and Nuclear Disarmament* 2 (1): 357–369. doi:10.1080/25751654.2019.1592708.

Yoshida, F. 2018. “Japan Should Scrutinise the Credibility of the US Nuclear Umbrella: An Interview with Shigeru Ishiba.” *Journal for Peace and Nuclear Disarmament* 1 (2): 464–473. doi:10.1080/25751654.2018.1507414.

Zhang, H., and K. Wang. 2019. “A Nuclear-Armed North Korea without ICBMs: The Best Achievable Objective.” *The Nonproliferation Review* 26 (1–2): 143–153. doi:10.1080/10736700.2019.1596574.