"This report carries several implications for decision-makers seeking to promote sound policies on nuclear disarmament. It shows that irreversibility mandates scrutiny of both advanced civilian nuclear powers and future former nuclear-armed states alike. [. . .] Analysis suggests a preventive approach based upon a series of overlapping layers of monitoring and verification. None of these layers will be perfect independently. But in the aggregate, they may well collectively reduce the threat of militarily significant non-compliance to politically acceptable levels."

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REPORT

Layered Verification: Irreversible Nuclear Disarmament and Highly Latent Nuclear States

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Introduction

"Irreversibility" as a nuclear disarmament concept made its debut in the Final Document of the 2000 Review Conference of the Nuclear Non-Proliferation Treaty (NPT). Its Section 15 lists irreversibility as the fifth of thirteen practical steps for implementing the NPT's Article VI nuclear disarmament commitments. The text reads: "The principle of irreversibility to apply to nuclear disarmament, nuclear and other related arms control and reduction measures".[1] Elsewhere, the final document discusses the imperative to irreversibly transfer nuclear materials from military to civilian activities, and the need for the verification thereof. This marked the beginning of serious thinking about irreversible nuclear disarmament, or IND.

Subsequent uses of the phrase have been widespread in multilateral nuclear diplomacy. IND discussions have since appeared in further NPT documents, in the Treaty on the Prohibition of Nuclear Weapons (TPNW), and in statements from groups such as the P5, the Non-Aligned Movement (NAM), and the New Agenda Coalition (NAC).[2] These concepts have even made it into North Korean Supreme Leader Kim Jong Un's lexicon.[3] Likewise, attempts to study IND implementation have attracted support from the British, Norwegian, and Swiss Foreign Ministries, and beyond, resulting in several notable research studies.[4] There were even recently three special issues of the *Journal for Peace and Nuclear Disarmament* focussing on IND.[5]

Defining irreversibility has, however, been a tall order and raised pivotal questions that remain unsettled. These include: Is it even really possible to completely eliminate the *potential* for nuclear armament? This puzzle has required much creative thinking from the arms control community. For example, Cliff, Elbahtimy, and Persbo introduced the idea of irreversibility as a spectrum ranging from low-level dismantlement and storage of weapons to total abandonment and destruction of state nuclear weapons complexes.[6] The authors are, in this sense, talking about different degrees of irreversibility. These discussions are likely to continue for some time into the future.

This report does not take a strong position on the thorny issue of defining irreversibility. But it does conceive of the idea as managing nuclear latency and accordingly operates under a few central assumptions worth clarifying at the outset:

1. **The premise of IND must be to eliminate pathways to weaponisation.**
2. **Irreversibility requires a continuous commitment to monitoring and verification.**
3. **IND is not a purely scientific–technical problem; it requires political will.**

With these points in mind, let us now consider the problem of IND and nuclear latency. This latter phrase has also garnered much interest from diplomats, scientists, and researchers in recent years. It refers to high civilian nuclear fuel cycle capability levels that may enable the development of nuclear arms—subject to state decisions to pursue the bomb. Like irreversibility, latency is often subject to definitional disagreement. Some scholars view it as a binary category, with latency granted the moment a country builds a single uranium enrichment or plutonium reprocessing (ENR) facility of a certain operational scale.[7] Others, including myself,

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1 Final Document of the 2000 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), NPT/CONF.2000/28 (Parts I and II), May 2020, p. 14, https://front.un-arm.org/wp-content/uploads/assets/WMD/Nuclear/pdf/finaldocs/2000%20-%20NY%20-%20NPT%20Review%20Conference%20-%20Final%20Document%20Parts%20I%20and%20II.pdf.

2 The five Permanent Members of the UN Security Council are also the five NPT-designated Nuclear Weapon States (NWS) by virtue of having "manufactured and exploded a nuclear weapon or other nuclear explosive device prior to 1 January 1967". Sometimes these countries make statements as the P5; other times they do so as the five NWS. I refer to them herein as the P5 for simplicity. For the full text see Treaty on the Non-Proliferation of Nuclear Weapons (NPT), Art. IX, 10485 *UNTS* 729, 5 March 1970, https://treaties.un.org/doc/Publication/UNTS/Volume%20729/volume-729-I-10485-English.pdf.

3 Hassan Elbahtimy, "Approaching Irreversibility in Global Nuclear Politics", *Journal for Peace and Nuclear Disarmament*, Vol. 6, No. 2 (2023), p. 200, https://doi.org/10.1080/25751654.2023.2295595.

4 See, for example, Stockholm International Peace Research Institute (SIPRI), "Irreversibility in Nuclear Disarmament—Political, Legal, Societal and Military–Technical Aspects", 2011; and David Cliff, Hassan Elbahtimy, and Andreas Persbo, "Irreversibility in Nuclear Disarmament: Practical Steps Against Nuclear Rearmament", Verification Research, Training and Information Centre (VERTIC), September 2011, http://www.vertic.org/media/assets/Publications/Irreversibility_Report_Sept_2011.pdf. For a recent discussion of official British and Norwegian views on the issue see "Irreversibility in the Context of the Treaty on the Non-Proliferation of Nuclear Weapons: Recommendations for the 10th Review Conference of the Parties to the Treaty", working paper submitted by Norway and the United Kingdom of Great Britain and Northern Ireland, NPT/CONF.20/WP.16, 8 November 2021, https://undocs.org/NPT/CONF.2020/WP.16.

5 *Journal for Peace and Nuclear Disarmament*, Vol. 6, No. 2 (2023), https://www.tandfonline.com/toc/rpnd20/6/2; *Journal for Peace and Nuclear Disarmament*, Vol. 7, No. 1 (2024), https://www.tandfonline.com/toc/rpnd20/7/1; *Journal for Peace and Nuclear Disarmament*, Vol. 7, No. 2 (2024), https://www.tandfonline.com/toc/rpnd20/7/2.

6 Cliff, Elbahtimy, and Persbo, "Irreversibility in Nuclear Disarmament", p. 47.

7 Matthew Fuhrmann and Benjamin Tkach, "Almost Nuclear: Introducing the Nuclear Latency Dataset", *Conflict Management and Peace Science*, Vol. 32, No. 4 (2015), pp. 443–461, https://doi.org/10.1177/0738894214559672;

argue that latency exists along a continuum of nuclear capability. That is, a state's nuclear progression toward mastering the fuel cycle determines whether it is in a "danger zone" for proliferation or not.[8] Latency is fundamentally a technical concept, but it is also a potential enabler of political nuclear hedging behaviour by states.

Regardless of one's definition, latency is particularly controversial in diplomatic discussions of IND. Indeed, both Article IV of the NPT and the Preamble to the TPNW emphasise States Parties' "inalienable right" to peaceful civilian nuclear energy.[9] Many nuclear-weapon-free zones (NWFZs) do so as well. Latency is not proscribed by international law, despite the dual-use nature of many civilian nuclear technologies. This means that high levels of nuclear latency are both permissible and compliant with these various multilateral treaties. As global interest in civilian nuclear power as a tool for energy independence and combatting climate change increases, so too will levels of nuclear latency.[10] Attempts to manage latency are therefore often seen as "disarming the disarmed" or perpetuating double standards within the global non-proliferation regime.

On the one hand, it may be appealing to see nuclear latency as an effective non-proliferation device. Several academics have postulated that a latent "hedge" may actually be sufficient to enhance a state's own coercive capabilities.[11] On the other hand, from an IND perspective, having states that are on the threshold of being able to develop the bomb is hardly an ideal scenario. The practice of deterrence with nuclear latency often involves an implicit or explicit threat to proliferate if the state is tested or its red lines are crossed.[12] These risks seem all the more worrisome given other scholarship suggesting that civilian nuclear programmes make states vulnerable to coercion.[13] That countries might convert their peaceful nuclear energy programmes into a drive for the bomb is antithetical to the idea of latency as a non-proliferation strategy.

Controlling completed nuclear arsenals is therefore insufficient for reaching and then maintaining a world in which nuclear disarmament is irreversible. Thinking about irreversibility requires attention to both the demand- and the supply-side of the nuclear disarmament equation, or the desirability and feasibility of disarmament.[14] The former (demand-side) is a more difficult proposition than the latter (supply-side), requiring close monitoring of global and regional security environments. This, however, is somewhat outside the scope of this report. Instead, I address here the latter, or how to control the hedge of nuclear latency from an IND perspective, which is both a political and technical problem. Persbo has written—correctly, in my view—that this necessitates a focus on material, capital, and labour.[15]

This report proceeds along these lines in six sections. First, I introduce various concepts at the intersection of nuclear latency and irreversibility of disarmament. My analysis shows that there are currently significant gaps and limitations in policy and technical knowledge and literature about eliminating pathways to the bomb. Second, I attempt to increase understanding of these dilemmas by laying out the problems of latency for IND in the context of a synthetic "worst-case" scenario. I then work to develop a framework of "layered verification", consisting of multiple interlocking mechanisms to detect and deter attempts to cross the nuclear threshold. Section three thus discusses layering of international policies for strengthening the non-proliferation regime that would be helpful in managing the trend

and Rupal N. Mehta and Rachel E. Whitlark, "The Benefits and Burdens of Nuclear Latency", *International Studies Quarterly*, Vol. 61, No. 3 (2017), pp. 517–528, https://doi.org/10.1093/isq/sqx028.

8 Stephen Herzog, "The Nuclear Fuel Cycle and the Proliferation 'Danger Zone'", *Journal for Peace and Nuclear Disarmament*, Vol. 3, No. 1 (2020), pp. 60–86, https://doi.org/10.1080/25751654.2020.1766164.

9 NPT, Art. IV; and Treaty on the Prohibition of Nuclear Weapons (TPNW), Preamble, A/CONF.229/2017/8, 7 July 2017, https://treaties.un.org/doc/Treaties/2017/07/20170707%2003-42%20PM/Ch_XXVI_9.pdf.

10 Steven E. Miller and Scott D. Sagan, "Nuclear Power Without Nuclear Proliferation", *Dædalus*, Vol. 138, No. 4 (2009), pp. 7–18, https://doi.org/10.1162/daed.2009.138.4.7.

11 Fuhrmann and Tkach, "Almost Nuclear"; Tristan A. Volpe, "Atomic Leverage: Compellence with Nuclear Latency", *Security Studies*, Vol. 26, No. 3 (2017), pp. 517–544, https://doi.org/10.1080/09636412.2017.1306398; and Tristan A. Volpe, *Leveraging Latency: How the Weak Compel the Strong with Nuclear Technology* (Oxford: Oxford University Press, 2023).

12 See, for example, Matthew Fuhrmann, *Influence without Arms: The New Logic of Nuclear Deterrence* (Cambridge: Cambridge University Press, 2024).

13 Mehta and Whitlark, "The Benefits and Burdens of Nuclear Latency"; Jeff D. Colgan and Nicholas L. Miller, "Rival Hierarchies and the Origins of Nuclear Technology Sharing", *International Studies Quarterly*, Vol. 63, No. 2 (2019), pp. 310–321, https://doi.org/10.1093/isq/sqz002; Rebecca Davis Gibbons, "Supply to Deny: The Benefits of Nuclear Assistance for Nuclear Nonproliferation", *Journal of Global Security Studies*, Vol. 5, No. 2 (2020), pp. 282–298, https://doi.org/10.1093/jogss/ogz059; Lisa Langdon Koch, "Holding All the Cards: Nuclear Suppliers and Nuclear Reversal", *Journal of Global Security Studies*, Vol. 7, No. 1 (2022), ogab034, https://doi.org/10.1093/jogss/ogab034; and Eliza Gheorghe, "The Spoilers from Within: Allies and Export Controls", *Journal of Strategic Studies*, Vol. 48, No. 3 (2025), pp. 627–657, https://doi.org/10.1080/01402390.2025.2454706.

14 Stephen Herzog, "Beyond Nuclear Deterrence", *Science*, Vol. 378, No. 1616 (2022), p. 115, https://doi.org/10.1126/science.adf2194.

15 Andreas Persbo, "Latent Nuclear Power, Hedging, and Irreversibility", in Joseph F. Pilat, ed., *Nuclear Latency and Hedging: Concepts, History, and Issues* (Washington, DC: Woodrow Wilson Center, 2019), pp. 43–72, https://www.wilsoncenter.org/sites/default/files/media/documents/book/nuclear_latency_and_hedging_-_concepts_history_and_issues.pdf.

towards increased latency. Many of these policy prescriptions will inevitably be well-known to readers, but the synthetic case sheds new light and relevance on them. I further develop the layered framework in section four by describing potential country-specific monitoring and verification strategies. This framework builds on the legal infrastructure of the Joint Comprehensive Plan of Action (JCPOA), popularly known as the Iran Nuclear Deal. It emphasises the importance of global standards and tailor-made solutions for addressing emerging nuclear proliferation challenges. Such policies are probably technically feasible, but ultimately, subject to political and financial constraints that must likewise be addressed. In section five, I address issues of cost and political will to implement a layered verification approach to irreversibility. I conclude with lessons for IND policy and research.

Taken together, this report carries several implications for decision-makers seeking to promote sound policies on nuclear disarmament. It shows that irreversibility mandates scrutiny of both advanced civilian nuclear powers and future former nuclear-armed states alike. The patchwork of extant solutions for managing nuclear latency is oftentimes specific to individual cases; these policy solutions may produce best practices but not silver bullets. Instead, my analysis suggests a preventive approach for maintaining IND based upon a series of overlapping layers of monitoring and verification. None of these layers will be perfect independently. But in the aggregate, they may well collectively reduce the threat of militarily significant non-compliance to politically acceptable levels. Verification of IND will be financially expensive and by necessity involve considerable new investments. But it is almost certainly cheaper than maintaining today's deterrent postures, with nine states' arsenals collectively containing approximately 12,241 warheads and omnipresent risks of nuclear war.[16]

Concepts and Research Limitations

In an irreversibly disarmed world, highly latent nuclear states will fundamentally come in two different categories. These two types of states are described in Table 1. First, states that are establishing and developing their civilian nuclear fuel cycle will—whether they intend to or not—**increase their capabilities and ease of proliferating**. There are currently 32 states with active nuclear energy programmes; numerous additional countries with shutdown or decommissioned facilities; and rising newcomer states like Bangladesh, Egypt, and Türkiye that have nuclear power plants under construction.[17] A focus on latency will become increasingly relevant given growing world interest in nuclear power—particularly in the Global South—for energy independence and climate change mitigation.[18] Second, states that have dismantled their nuclear weapons programmes will also then become highly latent given past investments in the infrastructure and knowledge to produce the bomb. In some ways, this means that future disarmed countries may bear some resemblance to today's latent nuclear states like Germany, Iran, Japan, South Korea, and others. There has, however, been only limited work investigating irreversibility and nuclear latency.[19] Systematic research into IND and nuclear weapons complexes is more common.[20]

Regardless of the contentious nature of discussions over IND and nuclear latency, close attention is required to states with advanced civilian nuclear capabilities. Lessons from managing nuclear latency may shed light on how to implement and verify IND in tomorrow's disarmed nuclear states. Additionally, as I discussed above, an ideal situation for global IND would be to not have numerous states that are a "screwdriver's turn" away from nuclear proliferation.[21] Stated differently, there will be inevitable structural

[16] Hans M. Kristensen, Matt Korda, Eliana Johns, and Mackenzie Knight, "Estimated Global Nuclear Warhead Inventories, 2025", Federation of American Scientists, 26 March 2025, https://fas.org/initiative/status-world-nuclear-forces.

[17] International Atomic Energy Agency (IAEA), "Power Reactor Information System (PRIS)", accessed 12 August 2025, https://pris.iaea.org/PRIS/home.aspx. This country count includes 31 members of the United Nations with the addition of Taiwan.

[18] Robert H. Socolow and Alexander Glaser, "Balancing Risk: Nuclear Energy & Climate Change", *Dædalus*, Vol. 138, No. 4 (2009), pp. 31–44, https://doi.org/10.1162/daed.2009.138.4.31; R. Cameron and J.H. Keppler, "Security of Energy Supply and the Contribution of Nuclear Energy", *NEA News*, Vol. 28, No. 2 (2010), pp. 4–8, https://www.oecd-nea.org/nea-news/2010/28-2/NEA-News-28-2-2-opinions.pdf; and M.D. Mathew, "Nuclear Energy: A Pathway Towards Mitigation of Global Warming", *Progress in Nuclear Energy*, Vol. 143 (2022), 104080, https://doi.org/10.1016/j.pnucene.2021.104080.

[19] For an exception see Persbo, "Latent Nuclear Power, Hedging, and Irreversibility".

[20] See, for example, Hassan Elbahtimy and Ross Peel, "Nuclear Weapons Production Complexes in a Disarmed World", *Journal for Peace and Nuclear Disarmament*, Vol. 6, No. 2 (2023), pp. 263–291, https://doi.org/10.1080/25751654.2023.2292348; and Nick Ritchie, "Irreversibility and Nuclear Disarmament: Unmaking Nuclear Weapon Complexes", *Journal for Peace and Nuclear Disarmament*, Vol. 6, No. 2 (2023), pp. 218–243, https://doi.org/10.1080/25751654.2023.2282737.

[21] This language comes from a discussion of Iran's uranium enrichment programme in David E. Sanger and Ashley Parker, "Romney Struggles in Explaining Iran Policy", *The New York Times*, 14 September 2012, https://www.nytimes.com/2012/09/15/us/politics/romney-struggles-to-distinguish-iran-red-line-from-obamas.html.

Table 1. Typology of Highly Latent Nuclear States

Type	Potential Motivations	Nuclear Capabilities	
Advanced Civilian Nuclear Powers	• Energy Independence • Climate Change Mitigation • Nuclear Hedging	• Uranium Enrichment • Plutonium Reprocessing • Weaponisation Knowledge	? ? ?
Former Nuclear-Armed States	• Civilian Nuclear Energy • Nuclear Hedging/Reconstitution	• Uranium Enrichment • Plutonium Reprocessing • Weaponisation Knowledge	? ? ✓

similarities between both of these types of states; each requires monitoring and verification in order to eliminate pathways to the bomb.

Table 1 shows the potential for actual—or at least observational—equivalence between advanced civilian nuclear powers and future disarmed nuclear states. The former group of states may pursue front-end uranium enrichment for eventual reactor fuel fabrication or back-end plutonium reprocessing to maintain a closed fuel cycle. In both cases, these ENR activities could help a state become more energy self-sufficient and less dependent on external suppliers. Whether the state seeks to hedge toward the bomb is thus largely irrelevant, as the attainment of nuclear latency is agnostic to potential motivations. In addition, peaceful security conditions that permit nuclear forbearance may not be permanent. A state that has eliminated its arsenal of nuclear weapons may or may not retain its ENR facilities. Yet, knowledge of fuel cycle mastery and weaponisation will remain among at least a generation of technical experts. By contrast, even though many multilateral nuclear treaties prohibit research and development of nuclear devices, weaponisation activities in civilian nuclear powers are difficult to observe absent credible intelligence.[22] The bottom line is that each type of highly latent nuclear state may have commonalities.

The historical record provides some useful insights into the implementation of IND concepts among latent nuclear states. I would identify three examples that offer lessons for irreversibility. They are the creation and ongoing operation of the Brazilian–Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), the Iran Nuclear Deal, and the unilateral nuclear disarmament of South Africa.

The creation of ABACC was the product of rapprochement between former military rivals, Argentina and Brazil, after their democratisation.[23] Each had made considerable investments in the nuclear fuel cycle. Following a series of confidence-building meetings of their respective heads of state and other high-ranking officials from the mid-1980s onward, ABACC inspections began in September 1992.[24] They continue to this day. The agency's inspectors come from both countries, and the organisation's mandate is to foster transparency about each sides' nuclear intentions. The two states, ABACC, and the International Atomic Energy Agency (IAEA) also drafted the Quadripartite Agreement, which entered into force in March 1994. The agreement combined ABACC and IAEA safeguards inspections into a single process.[25] Officials in Buenos Aires and Brasília can today be confident that their neighbour is not intending to cross the nuclear threshold, despite a history of uranium enrichment and spent fuel reprocessing in each country. Indeed, mutual threat reduction and transparency activities among rivals have helped to attenuate both regional and international concerns about nuclear proliferation.[26] There is rarely talk of a potential Argentina–Brazil nuclear security dilemma as a result, except as an artifact of the historical record.

[22] Alexander K. Bollfrass, "Separating Isotope Facts from Fallacies: Nuclear Weapons Proliferation in the Eyes of Three Intelligence Communities", *Intelligence and National Security*, Vol. 37, No. 3 (2022), pp. 377–401, https://doi.org/10.1080/02684527.2021.1992153.

[23] See Mariana Oliveira do Nascimento Plum and Carlos Augusto Rollemberg de Resende, "The ABACC Experience: Continuity and Credibility in the Nuclear Programs of Brazil and Argentina", *The Nonproliferation Review*, Vol. 23, No. 5–6 (2016), pp. 575–593, https://doi.org/10.1080/10736700.2017.1339402; and Carlo Patti, *Brazil in the Global Nuclear Order, 1945–2018* (Baltimore: Johns Hopkins University Press, 2021).

[24] José Goldemberg and Harold A. Feiveson, "Denuclearization in Argentina and Brazil", *Arms Control Today*, Vol. 24, No. 2 (1994), pp. 10–14, https://www.jstor.org/stable/23625089.

[25] John R. Redick, Julio C. Carasales, and Paulo S. Wrobel, "Nuclear Rapprochement: Argentina, Brazil, and the Nonproliferation Regime", *The Washington Quarterly*, Vol. 18, No. 1 (1995), pp. 107–122, https://doi.org/10.1080/01636609509550135.

[26] Author interview with Sergio Solmesky, Assistant Secretary General of the Brazilian–Argentine Agency for Accounting and Control of Nuclear Materials (ABACC), Rio de Janeiro, 14 August 2017; and author interview with Marco Marzo, Secretary General of ABACC, Rio de Janeiro, 1 August 2019.

The Iran Nuclear Deal, or JCPOA, showcases another set of possible best practices with relevance to latent state challenges to IND. Before its untimely collapse, among arms controllers, the deal had a reputation for being highly successful during its implementation.[27] The JCPOA's provisions are extensive, intrusive, and *primarily* pertain to freezing the Islamic Republic's uranium enrichment programme in exchange for economic sanctions relief.[28] Such parameters include: a reduction in Iran's installed gas centrifuges (by two-thirds), limitations on the quality (3.67%) and quantity (from 10,000 kilograms to 300) of its low-enriched uranium, and a cessation of operations at the previously undeclared Fordow enrichment plant—located in a hardened underground site.[29] But the deal did not stop there, as it allowed IAEA inspectors unprecedented access to Iran's facilities of concern. Under the JCPOA, Iran not only implemented the Additional Protocol, but the agency was able to visit sites covering Tehran's entire fuel cycle and supply chain—from mines for uranium ore to facilities that make the tools to build centrifuges.[30] New technologies and techniques of on-site and remote monitoring, like the online enrichment monitor, were deployed by the IAEA in support of its mission.[31] The JCPOA revealed that, with support from its Board of Governors for an expanded mandate, the IAEA could, in fact, contain nuclear latency through its safeguards inspections. Its multiple mechanisms for monitoring and verifying Iran's nuclear activities provided sufficient confidence about Tehran's intentions. The deal's rollback likely contributed to the recent Israeli and US counter-proliferation strikes on Iran.

Finally, the elimination of South Africa's nuclear weapons during the transition away from the Apartheid system points to some further lessons for irreversibility.[32] In 1977, South Africa is known to have constructed a nuclear test site in the Kalahari Desert.[33] The country initially had very limited fissile materials available and, as Heinonen writes, "was also not known to have developed an implosion-type design requiring testing".[34] Pretoria built its first gun-type, air-delivered gravity bomb in 1979, using highly-enriched uranium (HEU). When South Africa dismantled its arsenal and then acceded to the NPT in 1991, six such weapons were reported to have been destroyed. However, this information only became public on 24 March 1993, when President F. W. de Klerk told his parliament: "[A]t one stage South Africa did develop a limited nuclear deterrent capability", which, "early in 1990 final effect was given to decisions that all the nuclear devices should be dismantled and destroyed".[35] The Apartheid regime's relations with the IAEA had been fraught because of its international isolation.[36] IAEA inspectors did begin to suspect that South Africa might have had a nuclear weapons programme once they began safeguards inspections in 1991 pursuant to NPT Article III. But broadly speaking, the day the international community learned that Pretoria had a nuclear arsenal was the same day they learned it had been eliminated. The agency eventually did an evaluation of South Africa's facilities and claims. Still, Pretoria's disarmament process was not particularly transparent, and the remaining fuel cycle facilities and institutional knowledge in the country means that it maintains its nuclear latency.

Importantly, the ABACC process, the JCPOA, and South Africa's nuclear disarmament were all **specific solutions to specific problems**. Each one certainly does offer some lessons that could help researchers think

[27] See, for example, Mark Fitzpatrick, "Assessing the JCPOA", in Mark Fitzpatrick, Michael Elleman, and Paulina Izewicz, *Uncertain Future: The JCPOA and Iran's Nuclear and Missile Programmes*, *Adelphi Series*, Vol. 57, No. 466–467 (London: International Institute for Strategic Studies, 2017), pp. 19–60, https://doi.org/10.1080/19445571.2017.1555914.

[28] Seyed Hossein Mousavian and Mohammad Mehdi Mousavian, "Building on the Iran Nuclear Deal for International Peace and Security", *Journal for Peace and Nuclear Disarmament*, Vol. 1, No. 1 (2018), pp. 169–192, https://doi.org/10.1080/25751654.2017.1420373.

[29] Joint Comprehensive Plan of Action and its Annexes, 14 July 2015, https://www.europarl.europa.eu/cmsdata/122460/full-text-of-the-iran-nuclear-deal.pdf.

[30] US White House, Office of the Press Secretary, "Parameters for a Joint Comprehensive Plan of Action Regarding the Islamic Republic of Iran's Nuclear Program", 2 April 2015, https://obamawhitehouse.archives.gov/the-press-office/2015/04/02/parameters-joint-comprehensive-plan-action-regarding-islamic-republic-ir.

[31] Vincent Fournier and Miklos Gaspar, "New IAEA Uranium Enrichment Monitor to Verify Iran's Commitments Under JCPOA", IAEA, Office of Public Information and Communication, 16 January 2016, https://www.iaea.org/newscenter/news/new-iaea-uranium-enrichment-monitor-verify-iran's-commitments-under-jcpoa.

[32] For a detailed chronology of this case see Robin E. Möser, *Disarming Apartheid: The End of South Africa's Nuclear Weapons Programme and Accession to the Treaty on the Non-Proliferation of Nuclear Weapons, 1968–1991* (Cambridge: Cambridge University Press, 2024). See also Kjølv Egeland, "A Theory of Nuclear Disarmament: Cases, Analogies, and the Role of the Non-Proliferation Regime", *Contemporary Security Policy*, Vol. 43, No. 1 (2022), pp. 111–112, https://doi.org/10.1080/13523260.2021.1978159.

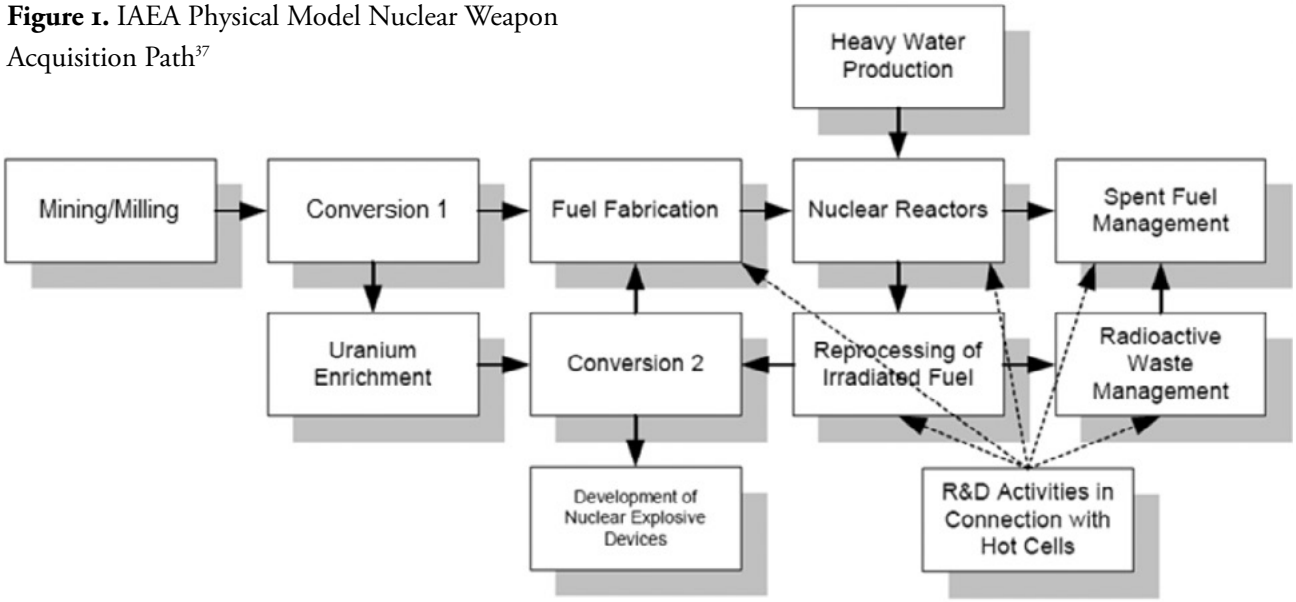
[33] Helen E. Purkitt and Stephen F. Burgess, *South Africa's Weapons of Mass Destruction* (Bloomington, Ind.: Indiana University Press, May 2005), pp. 51–81.

[34] Olli Heinonen, "Lessons Learned from Dismantlement of South Africa's Biological, Chemical, and Nuclear Weapons Programs", *The Nonproliferation Review*, Vol. 23, No. 1–2 (2016), p. 153, https://doi.org/10.1080/10736700.2016.1182685.

[35] Quoted in John W. de Villiers, Roger Jardine, and Mitchell Reiss, "Why South Africa Gave up the Bomb", *Foreign Affairs*, Vol. 72, No. 6 (1993), p. 98, https://doi.org/10.2307/20045817.

[36] See Jo-Ansie Van Wyk, "Atoms, Apartheid, and the Agency: South Africa's Relations with the IAEA, 1957–1995", *Cold War History*, Vol. 15, No. 3 (2015), pp. 395–416, https://doi.org/10.1080/14682745.2014.897697.

Figure 1. IAEA Physical Model Nuclear Weapon Acquisition Path[37]



about IND in the context of, for example, Germany's advanced nuclear fuel cycle. In addition to its three decommissioned reactors and 33 reactors in permanent shutdown, Berlin has uranium enrichment and fuel fabrication facilities, as well as past plutonium reprocessing research.[38] Similarly, these historical examples will likely be useful when pondering how to manage Japan's plutonium stockpile. A note from the country's Office of Atomic Energy Policy lays out its daunting scope:

> As of the end of 2023, the total amount of separated plutonium both managed within and outside of Japan was approximately 44.5 tons, approximately 8.6 tons of which was held domestically and the rest of approximately 35.8 tons was held abroad.[39]

This is considerably more plutonium than the stockpile of several nuclear-armed states.[40] It is also concerning given that the IAEA's conservative value for a significant quantity of plutonium—for which the production of a nuclear weapon cannot be excluded—is only eight kilograms.[41] None of the preceding historical cases offer an entirely ideal template for considering how to handle the technical and political sensitivities associated with the nuclear latency of Germany, Japan, and a number of further countries. If irreversibility is about managing nuclear latency, then additional brainstorming, research, and policymaking is appropriate.

A Worst-Case Scenario

The civilian nuclear fuel cycle has many different elements, as depicted in Figure 1. This diagram shows the possible pathways to getting to the bomb as laid out by analysts for the IAEA.

The IAEA's Physical Model illustrates the connection of both the front-end and the back-end of the nuclear fuel cycle to the development of nuclear explosive devices. The front-end consists of activities that occur before uranium fuel is introduced into a reactor: mining, milling, conversion, enrichment (if needed), and fuel fabrication. In pursuing a civilian nuclear energy programme, states thus increase their latent capability and technical proximity to the bomb. The key here is uranium enrichment to produce nuclear fuel, which can become problematic if states obtain higher concentrations of fissile isotope uranium-235—particularly as they get closer to an IAEA-designated significant quantity

[37] As depicted in Z. Liu and S. Morsy, "Development of the Physical Model", IAEA, Department of Safeguards, IAEA-SM-367/13/07, 2007, https://www-pub.iaea.org/MTCD/publications/PDF/ss-2001/PDF%20files/Session%2013/Paper%2013-07.pdf.

[38] IAEA, "Power Reactor Information System (PRIS)"; and IAEA, "Integrated Nuclear Fuel Cycle Information System (iNFCIS)", accessed 12 August 2025, https://www.iaea.org/resources/databases/integrated-nuclear-fuel-cycle-information-system-infcis.

[39] Japan Office of Atomic Energy Policy, Cabinet Office, "The Status Report of Plutonium Management in Japan - 2023", 16 July 2024, p. 1, https://www.aec.go.jp/bunya/04/plutonium/20240716_e.pdf.

[40] 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", 29 July 2022, https://fissilematerials.org/library/gfmr22.pdf.

[41] IAEA, "IAEA Safeguards Glossary", 2021 ed., *International Nuclear Verification Series*, No. 3, p. 23, https://www.iaea.org/sites/default/files/iaea_safeguards_glossary.pdf.

of 25 kilograms of uranium-235 within 90% weapons-grade material.[42] The back-end involves those activities associated with irradiated uranium fuel after its removal from a reactor. Attempts to reprocess fuel in a closed cycle require the separation of plutonium that can be used in a nuclear weapon. For this reason, ensuring IND requires monitoring and verification of fissile materials associated with latent states' ENR facilities. Nonetheless, the fuel cycle elements associated with the HEU and plutonium pathways to the bomb are not the only processes that will need to be scrutinised.

Breakout time as a policy concept refers to the period it would take a state to acquire enough fissile materials to produce a single nuclear weapon.[43] This makes sense because nuclear materials and ENR facilities are generally observable through monitoring, verification, and intelligence; weaponisation activities are usually not. For instance, the development of an implosion bomb design or experimentation with certain types of neutron generators would be indicative of a state's nuclear intentions. These activities are thus usually hidden and very well-concealed from the international community. Consequently, breakout time calculations assume simultaneous weaponisation activities. And it is not just states like Iran that have studied weaponisation. The relevant political science literature indicates that up to 35 states have been "potential proliferators" with advanced nuclear capabilities or aspirations to nuclearise.[44] Some states limited their activities to fissile material production, but others did, in fact, explore or experiment with weaponisation.[45] When managing nuclear latency and aiming for IND globally, it will be essential not to overlook potential bases of knowledge pertaining to weaponisation.

Weaponisation times have also almost certainly decreased since the days of horizontal nuclear proliferation by the P5. Today, simple designs for nuclear explosive devices are freely available on the internet, and generative artificial intelligence might also have a significant impact in reducing proliferation timelines.[46] Building the bomb obviously requires considerable work, technology, resources, and fissile materials to perfect and operationalise, but would-be proliferators are not starting "from scratch" in their designs. Additionally, there have been decades of black-market trade in nuclear weapons-related technologies and ideas. Pakistani scientist Abdul Qadeer Khan, or AQ Khan, reportedly offered to sell designs for nuclear weapons to Saddam Hussein's regime in Iraq in 1990.[47] Furthermore, the rise of additive manufacturing has led to fears that countries may "3D print the bomb" by producing components they are unable to acquire commercially.[48] In contemporary times, highly latent nuclear states that opt to translate their civilian capabilities into military programmes likely have some advantages in overcoming weaponisation hurdles that were unavailable in the past. The difficulty of observing many of these processes—absent excellent intelligence—suggests that an emphasis on knowledge management also matters for IND.

In sum, irreversibility should entail a focus on activities related to the uranium and plutonium paths, as well as weaponisation. There may be a compound effect, however, as latent nuclear states could pursue any combination of the three at the same time. The international community could therefore potentially be confronted with needing to pursue IND in a country with comparable weaponisation knowledge to South Africa, the plutonium stockpile of Japan, and

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42 IAEA, "IAEA Safeguards Glossary", p. 23.

43 Breakout time itself as a concept entails assumptions about the quantity and quality of fissile materials that are unlikely to match every would-be proliferator's bomb designs. It is best viewed as a heuristic rather than an exercise in "truth" or an exact calculation.

44 Sonali Singh and Christopher R. Way, "The Correlates of Nuclear Proliferation: A Quantitative Test", *Journal of Conflict Resolution*, Vol. 48, No. 6 (2004), pp. 859–885, https://doi.org/10.1177/0022002704269655; Dong-Joon Jo and Erik Gartzke, "Determinants of Nuclear Weapons Proliferation", *Journal of Conflict Resolution*, Vol. 51, No. 1 (2007), pp. 167–194, https://doi.org/10.1177/0022002706296158; Philipp C. Bleek, "When Did (and Didn't) States Proliferate? Chronicling the Spread of Nuclear Weapons", Harvard University, Project on Managing the Atom and Middlebury Institute of International Studies at Monterey, James Martin Center for Nonproliferation Studies, *Discussion Paper*, June 2017, https://www.belfercenter.org/publication/when-did-and-didnt-states-proliferate; Eliza Gheorghe, "Proliferation and the Logic of the Nuclear Market", *International Security*, Vol. 43, No. 4 (2019), pp. 88–127, https://doi.org/10.1162/isec_a_00344; and Stephen Herzog, "After the Negotiations: Understanding Multilateral Nuclear Arms Control", PhD diss., Yale University, 2021, p. 14, n7, https://elischolar.library.yale.edu/gsas_dissertations/58.

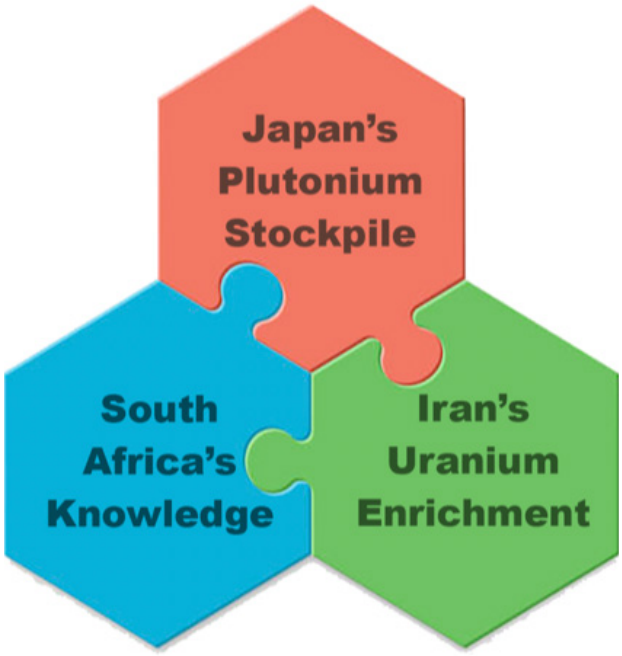
45 See, for example, Alexandre Debs and Nuno P. Monteiro, *Nuclear Politics: The Strategic Causes of Proliferation* (Cambridge: Cambridge University Press, 2017).

46 Jeffrey M. Kaplow and Ryan A. Musto, "Artificial Intelligence and the Future of Nuclear Weapons", in Philipp Hacker, ed., *Oxford Intersections: AI in Society*, advance online publication, 3 April 2025, https://doi.org/10.1093/9780198945215.003.0090.

47 David Albright and Corey Hinderstein, "Documents Indicate A.Q. Khan Offered Nuclear Weapon Designs to Iraq in 1990: Did He Approach Other Countries?", Institute for Science and International Security, *Report*, 4 February 2004, https://isis-online.org/isis-reports/detail/documents-indicate-a.q.-khan-offered-nuclear-weapon-designs-to-iraq-in-1990/12.

48 Matthew Kroenig and Tristan Volpe, "3-D Printing the Bomb? The Nuclear Nonproliferation Challenge", *The Washington Quarterly*, Vol. 38, No. 3 (2015), pp. 7–19, https://doi.org/10.1080/0163660X.2015.1099022; and Tristan A. Volpe, "Dual-Use Distinguishability: How 3D-Printing Shapes the Security Dilemma for Nuclear Programs", *Journal of Strategic Studies*, Vol. 42, No. 6 (2019), pp. 814–840, https://doi.org/10.1080/01402390.2019.1627210.

Figure 2. Synthetic Case Composition



the uranium enrichment capacity of Iran. Rather than considering each of these phenomena in isolation, I would argue that it is best to analyse a synthetic case. Figure 2 shows this essentially worst-case scenario. While the implementation of IND will have some differences across all latent countries, the synthetic case offers insights into thinking about a broader framework of monitoring and verification.

Strengthening the Nuclear Non-Proliferation Regime

As of 2022, the IAEA was already safeguarding 1,354 facilities and associated locations alongside 230,754 significant quantities of fissile material.[49] Because nuclear latency is a product of an expanding civilian nuclear fuel cycle, growing interest in nuclear energy will only increase these numbers in the future. While high levels of latency are permissible under the NPT, TPNW, and NWFZs, this does not mean that there is no role for the non-proliferation regime in latency monitoring and verification. This section thus highlights eight specific ways that existing institutions can play such a role, drawing inspiration from the synthetic case framework. Each of these layers works together by increasing the difficulty of proliferation, complementing the country-specific approaches described later. Table 2 summarises this section.

Table 2. Potential IND-Relevant Enhancements to the Non-Proliferation Regime

International Activity	Relevant Processes
1. Revive Fissile Material Cut-Off Treaty Discussions	• Uranium Enrichment • Plutonium Reprocessing
2. Universalisation of Additional Protocol	• Uranium Enrichment • Plutonium Reprocessing • Weaponisation
3. Leverage Innovation from Iran Nuclear Deal	• Uranium Enrichment • Plutonium Reprocessing • Weaponisation
4. International Spent Fuel Storage	• Plutonium Reprocessing
5. Tritium Freeze, Ban, or International Control	• Weaponisation
6. Prototype Cooperating National Facilities	• Weaponisation
7. Commercial Satellite Imagery Monitoring and Verification	• Uranium Enrichment • Plutonium Reprocessing
8. Improved Baseline Facility, Technology, and Material Declarations	• Uranium Enrichment • Plutonium Reprocessing • Weaponisation

First, a transparent and verifiable Fissile Material Cut-Off Treaty (FMCT) may be a politically combative subject, but it would be a considerable facilitator of IND. Recall that our synthetic case state has activities relevant to both pathways identified in the IAEA Physical Model shown in Figure 1. As Podvig has written, "a world free of nuclear weapons would be impossible without an effective ban on the production of fissile materials for weapons".[50] Proscribing fissile material production would be a useful step toward cutting off pathways to the bomb, in line with the concept of irreversibility.[51] There are, however, sharp disagreements among states about whether a treaty governing fissile materials should go further than an FMCT and also regulate and eliminate existing stockpiles of materials like the Japanese plutonium stocks—a characteristic of the synthetic case. In principle, the members of the Geneva-based Conference on Disarmament (CD)

[49] IAEA, "IAEA Safeguards in 2022", accessed 12 August 2025, https://www.iaea.org/sites/default/files/23/06/sg-implementation-2022.pdf.

[50] Pavel Podvig, "Taking Stock of the FMCT. A Discussion Paper", United Nations Institute for Disarmament Research, March 2024, https://unidir.org/wp-content/uploads/2024/03/UNIDIR_Fissile_Material_Cutoff_Treaty_Working_Paper_Draft_2024_03_23-1.pdf.

[51] See, for example, Harold A. Feiveson, Alexander Glaser, Zia Mian, and Frank N. Von Hippel, *Unmaking the Bomb: A Fissile Material Approach to Nuclear Disarmament and Nonproliferation* (Cambridge, Mass.: MIT Press, 2014).

have all agreed to negotiate on an FMCT since August 1998, but some members have conditioned the talks on disarmament and the prevention of an arms race in outer space.[52] These more intractable issues have produced deadlock at the CD, although there are questions about whether they are just convenient excuses to avoid the topic of fissile materials. But the world has changed quite a bit since 1998. The creation and entry-into-force of the TPNW has returned tensions over disarmament to the forefront of multilateral nuclear diplomacy.[53] There is heightened interest in discussing this subject matter, particularly outside the context of the Ban Treaty for many nuclear-armed states and their allies. Furthermore, concerns about anti-satellite weapons, fractional orbital bombardment systems, and even the deployment of nuclear arms in space have changed understandings about military space power.[54] These developments over the past few decades might enable a shift in diplomatic conversations toward a future breakthrough on the FMCT. Even if this is not the case, increased transparency and confidence-building measures about fissile material inventories will be an integral component of IND.

Second, efforts to universalise the Additional Protocol (AP) for more stringent safeguards agreements could be helpful in monitoring all components of the synthetic case. While the AP is voluntary, as the agency itself says, the AP's "additional tools of verification [. . .] significantly [increase] the IAEA's ability to verify the peaceful use of all nuclear material in States with comprehensive safeguards agreements".[55] A total of 144 states and Euratom—the European Atomic Energy Community—currently have an AP with the agency that has entered into force, and 12 states have signed one with the intention of doing so.[56] This is a high number of states, but it is far from universal and may not necessarily include our synthetic case country. Many AP holdouts are countries from the Global South that are resistant to the idea of being treated like they require additional surveillance. These states include some with non-trivial levels of nuclear latency like Argentina and Brazil. Current trends in the civilian nuclear marketplace also indicate why there is value in universalising the AP. While Western suppliers of nuclear technology have sometimes been apprehensive to engage in civilian nuclear trade with countries outside of the AP regime, Beijing and Moscow have rushed to fill the gap by creating a parallel "autocratic nuclear marketplace".[57] Egypt has not concluded an AP with the IAEA and has, in the past, not been fully compliant with its Comprehensive Safeguards Agreement (CSA). Yet, Cairo had little trouble securing Russian financing and finding prospective Chinese and Russian reactor suppliers for its El-Dabaa project. Similarly, Belarus does not have an AP in force, but Moscow financed the Astravets nuclear power plant that was built by the Russian state firm Atomstroyexport.[58] The AP's power to eliminate concerns about nuclear latency in such cases led Gibbons and Robinson to refer to it as "the strongest signal available to states that they support the nuclear nonproliferation regime and have benign nuclear intentions".[59]

Third, the Iran Nuclear Deal went well beyond the AP's provisions, with innovative elements that could be applied to future safeguards in support of IND. For example, the online enrichment monitor allowed for real-time monitoring of uranium enrichment levels in gas centrifuges. This process of sampling and analysis previously took three weeks or longer.[60] The expanded

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52 Ambassador Robert T. Grey, Jr., "Deadlocked and Waiting at the UN Conference on Disarmament", interviewed by Wade Boese, *Arms Control Today*, Vol. 30, No. 10 (2000), pp. 3–8, https://www.jstor.org/stable/23626847.

53 Naomi Egel and Steven Ward, "Hierarchy, Revisionism, and Subordinate Actors: The TPNW and the Subversion of the Nuclear Order", *European Journal of International Relations*, Vol. 28, No. 4 (2022), pp. 751–776, https://doi.org/10.1177/13540661221112611; and Rebecca Davis Gibbons and Stephen Herzog, "Nuclear Disarmament and Russia's War on Ukraine: The Ascendance and Uncertain Future of the Treaty on the Prohibition of Nuclear Weapons", in Rebecca Davis Gibbons, Stephen Herzog, Wilfred Wan, and Doreen Horschig, *The Altered Nuclear Order in the Wake of the Russia-Ukraine War* (Cambridge, Mass.: American Academy of Arts and Sciences, 2023), pp. 1–36, https://www.amacad.org/sites/default/files/publication/downloads/2023_Promoting-Dialogue_Altered-Nuclear-Order.pdf.

54 Daniel Porras, "Anti-Satellite Warfare and the Case for an Alternative Draft Treaty for Space Security", *Bulletin of the Atomic Scientists*, Vol. 75, No. 4 (2019), pp. 142–147, https://doi.org/10.1080/00963402.2019.1628470.

55 IAEA, "Safeguards Legal Framework: Additional Protocol", accessed 12 August 2025, https://www.iaea.org/topics/additional-protocol.

56 IAEA, "Status List: Conclusion of Additional Protocols", updated 30 June 2025, https://www.iaea.org/sites/default/files/20/01/sg-ap-status.pdf.

57 Nicholas L. Miller and Tristan A. Volpe, "The Rise of the Autocratic Nuclear Marketplace", *Journal of Strategic Studies*, Vol. 46, No. 6–7 (2023), pp. 1325–1363, https://doi.org/10.1080/01402390.2022.2052725.

58 Rebecca Davis Gibbons and Stephen Herzog, "Durable Institution Under Fire? The NPT Confronts Emerging Multipolarity", *Contemporary Security Policy*, Vol. 43, No. 1 (2022), p. 61, https://doi.org/10.1080/13523260.2021.1998294; Alexander K. Bollfrass and Stephen Herzog, "The War in Ukraine and Global Nuclear Order", *Survival*, Vol. 64, No. 4 (2022), pp. 12–13, https://doi.org/10.1080/00396338.2022.2103255; and Nicole Grajewski, "Russia and the Global Nuclear Order," CNA Corporation, *Occasional Paper*, March 2024, p. 14, https://www.cna.org/reports/2024/03/Russia-and-the-Global-Nuclear-Order.pdf.

59 Rebecca Davis Gibbons and Todd Robinson, "Twenty-Five Years Safer? Assessing the IAEA's Model Additional Protocol and Its Role in International Politics", *The Nonproliferation Review*, Vol. 28, No. 4–6 (2021), https://doi.org/10.1080/10736700.2022.2064516.

60 Fournier and Gaspar, "New IAEA Uranium Enrichment Monitor to Verify Iran's Commitments Under JCPOA".

Board of Governors' mandate for the IAEA to monitor Iran also led to improved seal technology, 89% more deployed surveillance cameras, a doubling of the agency's calendar days in the field, and the collection of 1.2 million open-source documents related to Tehran's programme.[61] While these developments may be viewed sceptically by states that resist entering into an additional agreement beyond their CSA with the IAEA, they do suggest new ways of monitoring highly latent nuclear states for IND purposes. These tools all increase the likelihood of detecting diversion from the civilian fuel cycle to military nuclear programmes.

Fourth, international spent fuel storage is another possible initiative for monitoring irreversibility among latent nuclear states. The creation of repositories of this nature would allow for the extraction of plutonium "for burning onsite, possibly in fast breeders with thorium as the fertile element".[62] Meanwhile, international staff could create new reactor fuel for states such as the subject of our hypothetical synthetic case in this report. This type of facility already exists, exemplified by Russia's Mining and Chemical Combine in Zheleznogorsk, which receives spent fuel shipments from countries with Russia-supplied reactors.[63] The complex is not truly internationally run, but it does offer an interesting model for thinking about how to cut off pathways to the bomb and enhance irreversibility. The fissile components of the burned-up fuel would be removed at such repositories before the provision of new fuel, thereby helping to manage nuclear latency.

Fifth, and shifting gears to the weaponisation component of our synthetic case, is thinking about how to freeze or ban the production of tritium, or place it under international control. Tritium is a reactor by-product used both to increase the yield of thermonuclear weapons and develop neutron initiators for nuclear devices. As Kalinowski has argued:

> Without sufficient tritium remaining [. . .] the second stage would probably not ignite and the yield of the thermonuclear warheads would basically be reduced to the unboosted yield of the fission primary. If this is around 1 kt, the yield reduction due to the lack of tritium would exceed a factor of 100.[64]

Kelley has also pointed out that a freeze on tritium production would be a promising step toward disarmament because the isotope's physical half-life is 12.33 years. This could result in a slow, verifiable process to reduce nuclear dangers that would likely be more politically palatable to many states than the TPNW's outright ban on the bomb.[65] And an exponential decrease in the available explosive yield of nuclear weapons may well make them considerably less attractive to latent states. It is, however, unclear if states that lack nuclear arsenals will be willing to give up their control of tritium because of its beneficial civilian applications, in for example, radioluminescent lighting.

Sixth, the Comprehensive Nuclear-Test-Ban Treaty's (CTBT) overlooked cooperating national facility (CNF) provision offers another monitoring mechanism.[66] In an IND world, ensuring that weaponisation has not occurred may mean enhanced detection and deterrence of nuclear test explosions. Roughly 90% of the treaty's 321 International Monitoring System (IMS) stations and 16 radionuclide laboratories are up and running, despite the treaty's non-entry-into-force.[67] There are still, however, some non-operational IMS stations located in countries like Egypt, Iran, Pakistan, Saudi Arabia, and elsewhere.[68] More stations essentially cannot be added to the IMS prior to the CTBT's entry-into-force. But the CNF provision allows states to fund data links and authentication of their own geophysical monitoring stations by the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization

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61 IAEA, "Verification and Monitoring in Iran", accessed 12 August 2025, https://www.iaea.org/newscenter/focus/iran.

62 US Office of Technology Assessment, "Nuclear Proliferation and Safeguards", June 1977, p. 172, https://apps.dtic.mil/sti/tr/pdf/ADA337748.pdf.

63 Nicole Jawerth, "Under One Roof: Russia's Integrated Strategy for Spent Fuel Management", IAEA, Office of Public Information and Communication, 2 August 2019, https://www.iaea.org/newscenter/news/under-one-roof-russias-integrated-strategy-for-spent-fuel-management.

64 Martin B. Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and Disarmament* (Boca Raton, Fla.: CRC Press, 2004), p. 32.

65 Robert E. Kelley, "Starve Nuclear Weapons to Death with a Tritium Freeze", SIPRI, *Backgrounder*, 28 August 2020, https://www.sipri.org/commentary/topical-backgrounder/2020/starve-nuclear-weapons-death-tritium-freeze.

66 For a detailed discussion of these potential facilities see Ola Dahlman, Svein Mykkeltveit, and Hein Haak, *Nuclear Test Ban: Converting Political Visions to Reality* (Dordrecht, Netherlands: Springer, 2009), p. 137; and Ola Dahlman, Jenifer Mackby, Svein Mykkeltveit, and Hein Haak, *Detect and Deter: Can Countries Verify the Nuclear Test Ban?* (Dordrecht, Netherlands: Springer, 2011), p. 202.

67 Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), "International Monitoring System Map", updated November 2024, https://www.ctbto.org/our-work/ims-map.

68 CTBTO, "Station Profiles", accessed 12 August 2025, https://www.ctbto.org/our-work/station-profiles.

(CTBTO). The data can be sent to the International Data Centre (IDC) in Vienna alongside IMS inputs.[69] Nuclear monitoring data that is authenticated and aggregated by international organisations has historically been seen as more credible by states.[70] An official CNF cannot be established until the treaty enters into force though, but there have been feasibility studies on prototype facilities and discussions on the matter between states and the CTBTO.[71] When thinking about nuclear disarmament and irreversibility, more internationally authenticated waveform and radionuclide data in the hands of the IDC for distribution to states would be a net positive. Very few states have the resources and national technical means (NTM) to conduct their own extensive nuclear explosion monitoring. CNFs could therefore help to increase confidence in IND and are likely necessary anyway given reports of increased activities at nuclear test sites worldwide.

Seventh, greatly increased availability of commercial satellite imagery could be operationalised for remote monitoring of our synthetic case state. Private sector investment into low earth orbit (LEO) satellites has increased the number of units, imagery resolution, and data availability.[72] This is probably unsurprising, since space launches over the past decade have risen by a factor of 25 amid decreased costs.[73] Companies like Maxar and Planet Labs now have the ability to image the entire world each day, representing a significant improvement from Cold War era satellite verification.[74] Interested parties with the requisite financial resources could increase their monitoring and verification capabilities. Such actors could be states, but non-governmental organisations like the Vienna-based Open Nuclear Network (ONN) show that societal verification can also be useful in monitoring latency.[75] Meanwhile, great powers could integrate commercial data with their satellite-based NTM and other forms of intelligence. Regardless, it is instructive to consider the limitations of these private sector developments for ensuring compliance with IND standards. Many of these technology firms do not share the same agenda as states, but rather, can be pressured to obscure or discontinue coverage of certain areas by governments. In this regard, recall, for example, SpaceX declining to allow Ukraine to use its Starlink satellites for the targeting of strikes against Russian forces operating in Crimea.[76] Further, satellite imagery may assist in identifying undeclared ENR facilities or pre- and post-detonation events and movements at nuclear test sites.[77] While satellite imagery can do little to assist the international community in detecting potential weaponisation activities taking place inside of facilities, the rise of these commercial capabilities might cause states to become more circumspect about what nuclear activities they are willing to pursue.

Eighth, much more research should focus on how to verify states' baseline facility, technology, and material declarations in the pursuit of an IND agenda. Perhaps the procedures that went into Chemical Weapons Convention (CWC) declarations of this nature could be useful. As it stands, there is some existing literature on baseline declarations and nuclear disarmament, but it generally pertains to states that have eliminated their nuclear arsenals.[78] Accordingly, these works discuss the

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69 Stephen Herzog, "The Nuclear Test Ban: Technical Opportunities for the New Administration", *Arms Control Today*, Vol. 47, No. 1 (2017), pp. 28–29, https://www.jstor.org/stable/90004325.

70 See, for example, Allison Carnegie and Austin Carson, "The Disclosure Dilemma: Nuclear Intelligence and International Organizations", *American Journal of Political Science*, Vol. 63, No. 2 (2019), pp. 269–285, https://doi.org/10.1111/ajps.12426.

71 Stephen Herzog, "A Policy Roadmap for Improved Comprehensive Test Ban Treaty Monitoring", in Mark F. Cancian, ed., *Project on Nuclear Issues: A Collection of Papers from the 2017 Conference Series and Nuclear Scholars Initiative* (Washington, DC: Center for Strategic and International Studies/Rowman & Littlefield, 2017), pp. 114–115, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3128707.

72 Steve Fetter and Jaganath Sankaran, "Emerging Technologies and Challenges to Nuclear Stability", *Journal of Strategic Studies*, Vol. 48, No. 2 (2024), pp. 252–296, https://doi.org/10.1080/01402390.2024.2433766.

73 United Nations Office for Outer Space Affairs, "Online Index of Objects Launched into Outer Space", accessed 12 August 2025, https://www.unoosa.org/oosa/osoindex/index.jspx.

74 Dominika Kunertova and Stephen Herzog, "Emerging and Disruptive Technologies Transform, but Do Not Lift, the Fog of War – Evidence from Russia's War on Ukraine", in Pentti Forsström, ed., *Russia's War Against Ukraine – Complexity of Contemporary Clausewitzian War, Series 2, Research Report*, No. 33 (Helsinki: Finnish National Defence University, 2024), pp. 146–161, https://doi.org/10.3929/ethz-b-000696795.

75 On societal verification see, for example, Sara Al-Sayed, "Revisiting Societal Verification for Nuclear Non-Proliferation and Arms Control: The Search for Transparency", *Journal for Peace and Nuclear Disarmament*, Vol. 5, No. 2 (2022), pp. 496–506, https://doi.org/10.1080/25751654.2022.2133336.

76 Tara Copp, "Elon Musk's Refusal to Have Starlink Support Ukraine Attack in Crimea Raises Questions for Pentagon", Associated Press, 12 September 2023, https://apnews.com/article/spacex-ukraine-starlink-russia-air-force-fde93d9a69d7dbd1326022ecfdbc53c2.

77 Final confirmation of a potential nuclear explosive test would, however, require accompanying radionuclide data.

78 See, for example, George Perkovich and James M. Acton, *Abolishing Nuclear Weapons*, *The Adelphi Papers*, Vol. 48, No. 396 (London: International Institute for Strategic Studies, 2008), https://www.tandfonline.com/toc/tadl19/48/396; Pavel Podvig and Joseph Rodgers, "Deferred Verification: Verifiable Declarations of Fissile-Material Stocks for Disarmament Purposes", *The Nonproliferation Review*, Vol. 26, No. 3–4 (2019), pp. 209–217, https://doi.org/10.1080/10736700.2019.1628414; and Mona Dreicer, "Baseline Declarations", in Malte Göttsche and Alexander Glaser, eds., *Toward Nuclear Disarmament: Building up Transparency and Verification* (Berlin: German Federal Foreign Office, 2021), pp. 14–25, https://inis.iaea.org/collection/NCLCollectionStore/_Public/53/104/53104391.pdf.

need to declare relevant weapons, materials, and production facilities. The declarations would also need to be inclusive of undeclared civilian or military facilities that are currently outside of IAEA safeguards. There are also discussions in the literature about starting with a narrow baseline declaration and gradually increasing its scope over time as a state's confidence in the process rises. All of this should be easier though for most highly latent nuclear states that are developing the civilian fuel cycle, as they are presumably operating safeguarded facilities. Put simply, their IND-related activities should already be known to the IAEA. One exception is minor actinide stocks, which are currently only subject to voluntary declarations.[79] An americium, curium, or neptunium bomb seems a lot less likely than one powered by HEU or plutonium, but ensuring irreversibility would suggest that these inventories should also be included in baseline declarations of latent states.

Country-Specific Approaches

The eight policies detailed in the above section form some of the interlocking layers of verification that could act as a sort of preventive medicine to manage nuclear latency. The end goal, of course, is to detect and deter non-compliance per the principle of irreversibility in nuclear disarmament. Monitoring and verification are imperfect, however, the international best practices described above would surely aid the task of dealing with the three elements of our synthetic case: uranium enrichment, plutonium reprocessing, and weaponisation knowledge.

Recall that ABACC, the JCPOA, and the disarmament of South Africa were specific solutions to specific problems. Highly latent nuclear states therefore also require tailored, country-specific approaches to layered verification. These mechanisms would act as a natural complement to efforts to bolster the nuclear nonproliferation regime. None of these layers are likely to work perfectly in isolation. But together, they should make it very difficult for a latent nuclear state to weaponise. This, too, may produce a deterrence by denial effect. As the odds of getting caught, shamed, and punished increase, non-compliance becomes more costly for would-be proliferators.

The IND verification framework should look to the Iran Nuclear Deal as a template for thinking about tailored, layered verification. Before the first administration of US President Donald Trump withdrew in 2018 and caused the agreement to unravel, the JCPOA's layered redundancies and intrusiveness were seen as a model by arms controllers. The deal was well-conceived. It contained rigid verification parameters at multiple nodes of the nuclear weapon acquisition path as laid out by the IAEA in Figure 1 above. Regarding uranium enrichment, these included: restrictions on Iran's centrifuge numbers and types at Natanz, limitations in enriched uranium quality and stockpiled quantity, access to facilities at every stage in the front-end of the fuel cycle, and closure of certain facilities like Fordow. With respect to the production of plutonium, the deal required: conversion of Iran's Arak heavy water reactor to eliminate weapons-grade plutonium production, shipment of spent nuclear fuel outside of the country, and an agreement to "indefinitely" forgo reprocessing and associated research.[80] Tehran had to refrain from weaponisation activities such as: developing certain explosives and neutron sources, pursuing various diagnostic systems used to assess nuclear test explosions, and computer modelling and simulation of nuclear explosive devices.[81]

These layers were designed specifically to cut off pathways to the bomb. Even if some of them had the potential to fail, Iran would have needed to construct considerable parallel hidden infrastructure to covertly turn violations of the JCPOA into militarily significant developments. This also would have presented risks, as the negotiation of the deal also involved the generation of international political will to punish non-compliance and a formal mechanism to do so via snapback sanctions. Of course, our synthetic case will have some commonalities but likely many differences with the Iranian context. Hence, there is a need to emphasise country-specific strategies.

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[79] Markus Preston, Erik Branger, Vitaly Fedchenko, Sophie Grape, Robert E. Kelley, Vaibhav Mishra, and Débora M. Trombetta, "Methodology for Multi-Parameter Evaluation of Barriers Against Proliferation of Minor Actinides", *Nuclear Technology*, Vol. 211, No. 3 (2024), pp. 548–569, https://doi.org/10.1080/00295450.2024.2342184.

[80] US White House, Office of the Press Secretary, "Parameters for a Joint Comprehensive Plan of Action Regarding the Islamic Republic of Iran's Nuclear Program".

[81] Kelsey Davenport, Daryl G. Kimball, and Greg Thielmann, "Solving the Iranian Nuclear Puzzle: The Joint Comprehensive Plan of Action", Arms Control Association, 4th ed., August 2015, pp. 20–22, https://www.armscontrol.org/reports/Solving-the-Iranian-Nuclear-Puzzle-The-Joint-Comprehensive-Plan-of-Action/2015/08.

Fortunately, recent work by Muti, Christopher, and Stott has explained some potential country-specific verification activities and their connection to irreversibility.[82] The authors discuss how verification can serve as a confidence-building measure, deter hedging by would-be proliferators, lead to voluntary transparency and monitoring, and prevent non-compliance. Likewise, they offer detailed tables listing verification measures relevant to fissile materials, decommissioning and dismantlement, and knowledge transfer.[83] I largely agree with their list and will not attempt to replicate their informative work, as my goal here is to think about a framework for managing nuclear latency in an IND context with characteristics of the synthetic case. But I would note that these authors consider the prospect of irreversibility in specific nuclear-armed states. My focus here on nuclear latency would require different tailored packages of these options to provide layering related to enrichment, reprocessing, and weaponisation activities.

There are a few areas where I think Muti, Christopher, and Stott's list of IND activities could be expanded upon in a nuclear latency context. One promising line of inquiry is nuclear archaeology that can assist in verifying baseline declarations. As Göttsche describes, accounting for uncertainty in fissile material stockpiles poses obstacles that are highly relevant to irreversibility:

> For example, while the United States stated in 1996 that 1.1 tons of plutonium entered the waste stream at the Hanford production site, a 2011 estimate assumes 4 tons. [. . .] As of 2009, the total plutonium stock that the United States is managing is 2.4 tons less than what it should possess according to its records. This quantity theoretically corresponds to hundreds of weapon-equivalents. It is, however, unclear whether any of this missing material ever existed.[84]

Latent nuclear states will obviously have potential fissile material inventories that are considerably smaller than that of the US, although the size of the Japanese separated plutonium stockpile indicates that the issue is not reserved only for nuclear-armed states. But the problem of potentially missing significant quantities of materials is real and poses challenges for verifying baseline declarations. Nuclear archaeology involves an examination of past operating records from enrichment facilities and reactors alongside the simulation of various reported parameter values.[85] These simulations, combined with sampling at the facility, could enable validation of the consistency of operating records and physical materials. As Fetter notes, it would not be easy "to invent a false operating history that is internally self-consistent".[86] This method of data analysis may indeed prove useful in detecting false records and undeclared periods of reactor and enrichment plant operations.

IND concepts applied to latent nuclear states also mean a focus on weaponisation. At first glance, the notion of such knowledge management initiatives may seem misplaced with states that have never built a nuclear arsenal. The concept of breakout time and its emphasis on fissile materials, however, assumes simultaneous weaponisation activities. Weaponisation to develop, manufacture, and maintain deliverable nuclear weapons is far more difficult to observe than the processes of acquiring uranium and plutonium fissile materials. It is possible that some hedging latent nuclear states may have covertly researched how to build the bomb, or even conducted experiments, in parallel with their civilian fuel cycle. The literature is rife with examples of states that did not cross the threshold but did at one point explore some elements of weaponisation.[87]

The typology provided in Table 1 earlier in this report classified latent states into two types: advanced civilian nuclear powers and future former nuclear-armed states. The latter group that maintained nuclear arsenals will naturally go through a transitory period as knowledge atrophies. Some of the difficulties that the US faces in attempting to restart plutonium pit production after more than three decades of not doing so is illustrative. Inactivity in certain processes of weaponisation can lead to atrophying knowledge among the workforce as well as in supporting industrial infrastruc-

[82] Alberto Muti, Grant Christopher, and Noel Stott, "The Role of Verification in Supporting Irreversible Nuclear Disarmament", *Journal for Peace and Nuclear Disarmament*, Vol. 6, No. 2 (2023), pp. 292–302, https://doi.org/10.1080/25751654.2023.2291892.

[83] Muti, Christopher, and Stott, "The Role of Verification in Supporting Irreversible Nuclear Disarmament", pp. 296–297.

[84] Malte Göttsche, "Nuclear Archaeology to Assess Fissile-Material Inventories for Nuclear Safety and Security, Transparency, and Disarmament", *The Nonproliferation Review*, Vol. 30, No. 1–3 (2024), pp. 131–132, https://doi.org/10.1080/10736700.2024.2314371.

[85] See, for example, Steve Fetter, "Nuclear Archaeology: Verifying Declarations of Fissile-Material Production", *Science & Global Security*, Vol. 3, No. 3–4 (1993), pp. 237–259, https://scienceandglobalsecurity.org/archive/sgs03fetter.pdf.

[86] Fetter, "Nuclear Archaeology", p. 239.

[87] See, for example, Debs and Monteiro, *Nuclear Politics*.

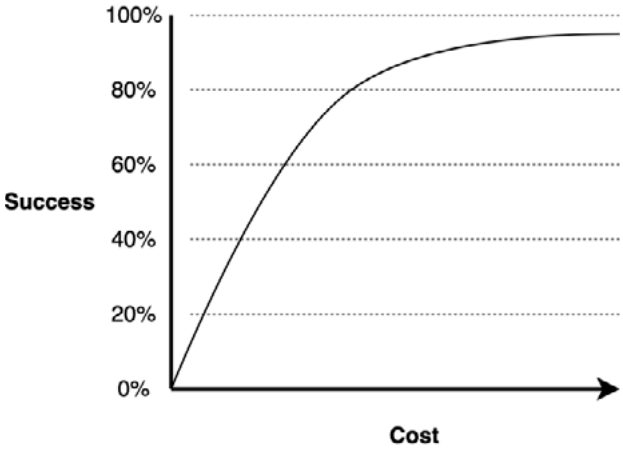
ture.[88] The speed of atrophy is likely to be much faster in a disarmed latent nuclear state than it is within an active nuclear weapons complex. During the transitory period while institutional knowledge and infrastructure slowly fades, monitoring and verification requirements will need to be more rigorous. Sunset clauses, where the provisions of the deal expire after an agreed period, would be appropriate for ensuring an adaptive level of verification given finite resources and threat assessment considerations.

The aforementioned pledges by Iran in the JCPOA not to pursue high-performance computer simulations that could assist in weaponisation may also prove useful in deterring proliferation. There is also a precedent for this type of restriction in multilateral nuclear diplomacy. During the CTBT negotiations, states such as Brazil unsuccessfully advocated for the treaty to prohibit experiments and simulations related to developing and improving nuclear devices.[89] Perhaps managing nuclear latency in an IND world might involve declarations of high-performance computing clusters with simulation power over a certain threshold. This would, naturally, raise difficult verification questions and predictable objections given their dual-use orientation and economic benefits, as well as their conventional military applications.[90] Verification and transparency that is seen to decrease states' security is also likely to face roadblocks at the arms control bargaining table.[91] Whether or not it is possible to verify pledges of simulation restraint, and how this could be operationalised, is outside the scope of this report.

Costs and Political Will

The vast number of specific measures that might be required in each case of layered, tailored monitoring and verification point to the impossibility of perfection. Yet, in the aggregate, multiple interlocking layers can drastically reduce the odds of undetected non-compliance down to very low levels.[92] The JCPOA case shows that these layers are particularly effective when coupled with the political will to verify and penalise instances of non-compliance. Actual rates of disarmament verifiability and trust in the process are, of course, different—one is technical while the other is psychological.[93] There is unfortunately sometimes a tendency among some policy-makers to ask verification specialists about how to achieve the unattainable goal of a 100% successful regime. Perfect can thus become the enemy of the good in terms of verification and prevent the realisation of meaningful arms control, non-proliferation, and disarmament initiatives.

Figure 3. Verification Success and Cost



The pursuit of perfection in achieving IND among latent nuclear states introduces a trade-off. Figure 3 provides a theoretical illustration of this dilemma for verification.

Verification is costly and produces diminishing marginal returns. As the costs of monitoring and verification increase, so too does success, asymptotically approaching 100%. But perfection is unattainable and costs rapidly increase; confidence in verification among policy-makers is also variable. The natural question is how much confidence in verification is enough, and how much will states be willing to pay? Through international and country-specific layering, however, built-in redundancies can create a system that is highly resilient and likely to prevent weaponisation—even with expected non-compliance. Perfection should

[88] Robert Peters and Maiya Clarke, "America's Ossified Nuclear Infrastructure Needs an Overhaul—Now", Heritage Foundation, Douglas and Sarah Allison Center for National Security, *Issue Brief*, No. 5338, 22 January 2024, pp. 4–5, https://www.heritage.org/sites/default/files/2024-01/IB5338.pdf.

[89] Conference on Disarmament (CD), "Final Record of the Six Hundred and Seventy-Fourth Plenary Meeting", CD.PV/674, Geneva, 10 March 1994, p. 22, https://digitallibrary.un.org/record/193830.

[90] Robert Johnston, "US Export Control Policy in the High Performance Computer Sector", *The Nonproliferation Review*, Vol. 5, No. 2 (1998), pp. 44–59, https://doi.org/10.1080/10736709808436706.

[91] Andrew J. Coe and Jane Vaynman, "Why Arms Control Is So Rare", *American Political Science Review*, Vol. 114, No. 2 (2020), pp. 342–355, https://doi.org/10.1017/S000305541900073X.

[92] See also Mareena Robinson Snowden, "Probabilistic Verification: A New Concept for Verifying the Denuclearization of North Korea", *Arms Control Today*, Vol. 49, No. 7 (2019), pp. 18–23, https://www.jstor.org/stable/26783920.

[93] See, for example, Wyn Q. Bowen, Hassan Elbahtimy, Christopher Hobbs, and Matthew Moran, *Trust in Nuclear Disarmament Verification* (Cham, Switzerland: Palgrave Macmillan, 2018).

probably not be the objective. Instead, verification should aim to detect and deter all instances of militarily significant non-compliance that would alter the international security environment and balance of power. After all, the continuous risk of nuclear war presented by maintaining large arsenals is almost certainly a greater cost to pay than the risk of a single bomb built by a non-compliant actor.

Whether layered verification of highly latent nuclear states is desirable ultimately comes down to questions of cost and political will. It is unclear which actors would be responsible for funding an expanded regime covering the group of latent nuclear states. Should it be the nuclear-armed states that crossed the threshold who foot the bill for the continuous monitoring and verification of IND? This is a continuous commitment, not an end state. Or, is the elimination of nuclear arsenals and the existential risks they pose a global common good that should be financially backed by all states in the international system? It will likely prove difficult to convince former nuclear-armed states to bear the full cost burden if highly latent states, like our synthetic case state, have fuel cycle activities that could enable nuclear proliferation.

At the same time, the costs of expanded verification activities in support of irreversibility may be more inexpensive than anticipated. For the year 2024–2025, the total annual budget of the IAEA was €751 million for its global monitoring activities.[94] This is less than the €763.3 million budget for the police department of the city of Vienna, where the agency is based.[95] Among the IAEA funds, €10.4 million were allocated for the entirety of the monitoring and verification mission in Iran, inclusive of the JCPOA.[96] By comparison, the cost of designing and manufacturing the UK's four new Dreadnaught-class fleet ballistic missile submarines may amount to up to £41 billion by the early 2030s.[97] And the estimated cost of expenditures for the US nuclear arsenal are $756 billion between 2023–2032, or over $75 billion annually.[98] Warhead dismantlement and facility decommissioning to reach IND would not be cheap for nuclear-armed states.[99] But in the long run, IND-related monitoring and verification will almost certainly be orders of magnitude more affordable than the long-term maintenance of nuclear arsenals, not to mention the incalculable costs associated with a nuclear war.

Political will is a related but separate issue. For the moment, it is understandable that latent nuclear states would be disinterested in—or actively opposed—to enhanced scrutiny of their civilian nuclear programmes. This will predictably be the case so long as the nuclear-armed states continue to maintain their arsenals. Once states start disarming and rolling back their nuclear weapon complexes, the continuous monitoring and verification for IND may be seen as a common good. Many countries in the Global South were sceptical of the IAEA until norms regarding responsible nuclear behaviour changed in the 1990s as a result of the crises over Iraqi and North Korean intentions. If evolving academic thinking about deterrence with nuclear latency becomes a formal part of states' security policies, the imperatives for enlarging the scope of IND may grow.

A final issue related to the politics of support for IND involves the implementing organisation.[100] Whether or not the IAEA's mandate could expand to include disarmament verification remains an open question, one that frequently invites controversy.[101] It is, for example,

94 IAEA, "The Agency's Programme and Budget 2024–2025", GC(67)/5, July 2023, p. v, https://www.iaea.org/sites/default/files/gc/gc67-5.pdf.

95 Austrian Federal Ministry of Finance, "Landespolizeidirektionen Wien" [State Police Department Vienna], 2024, https://service.bmf.gv.at/Budget/Budgets/VBB/de/2024/Home/Treemap?type=EV&houseHold=1&currency=MioEuro&filter=110201&showGrafic=True&showTable=false.

96 IAEA, Board of Governors, "Verification and Monitoring in the Islamic Republic of Iran in Light of United Nations Security Council Resolution 2231 (2015)", report by the Director General, GOV/2024/60/Rev.1, 19 November 2024, p. 1, https://www.iaea.org/sites/default/files/24/11/gov2024-61.pdf.

97 Claire Mills and Esme Kirk-Wade, "The Cost of the UK's Strategic Nuclear Deterrent", UK House of Commons Library, *Research Briefing*, No. 8166, 3 May 2023, p. 4, https://researchbriefings.files.parliament.uk/documents/CBP-8166/CBP-8166.pdf.

98 US Congressional Budget Office, "Projected Costs of U.S. Nuclear Forces, 2023 to 2032", July 2023, p. 1, https://www.cbo.gov/system/files/2023-07/59054-nuclear-forces.pdf.

99 Justin Alger and Trevor Findlay, "The Costs of Nuclear Disarmament", International Commission on Nuclear Non-Proliferation and Disarmament, September 2009, http://www.icnnd.org/Documents/Alger_Findlay_Cost_of_Disarmament.pdf.

100 See, for example, Leondardo Bandarra, Noah Mayhew, and Malte Göttsche, "The IAEA and Irreversibility: Addressing Political, Institutional, and Technological Verification Challenges in Former Nuclear-Armed States", *Journal for Peace and Nuclear Disarmament*, Vol. 7, No. 2 (2024), pp. 302–321, https://doi.org/10.1080/25751654.2024.2440115. And for a discussion of how IAEA safeguards may inform future nuclear disarmament verification see Mark Hibbs, "Irreversible Disarmament and Verification: Guidance from IAEA Safeguards", *Journal for Peace and Nuclear Disarmament*, Vol. 7, No. 2 (2024), pp. 322–332, https://doi.org/10.1080/25751654.2024.2421608.

101 Similarly, despite calls for the CTBTO to conduct a field inspection to verify the alleged closure of North Korea's Punggye-ri test site in 2018 and 2019, Russia and China raised questions about the organisation's mandate. Many states do not appear to be keen to see multilateral nuclear organisations push their mandate into disarmament territory. See, for example, Stephen Herzog, "After the Summit: A Next Step for the United States and North Korea", *Arms Control Today*, Vol. 48, No. 6 (2018), pp. 6–11, https://www.jstor.org/stable/90022977; Lassina Zerbo, "The Nuclear Test Ban and the Verifiable Denuclearization of North Korea", *Arms Control Today*, Vol. 48, No. 9 (2018), pp. 6–9, https://www.jstor.org/stable/90025939; and Mark Fitzpatrick, "How an International Inspection Agency Can Revive North Korean Détente", *Survival* Online, 31 May 2019, https://www.iiss.org/en/online-analysis/survival-online/2019/05/north-korea-nuclear-inspection-agency.

unclear what the relationship would be between the IAEA and the "competent international authority" to verify IND mentioned in the TPNW.[102] It is clear, however, that greater involvement by the IAEA in implementing activities related to IND will necessitate closer collaboration with representatives from nuclear-armed states. These experts served an important function during JCPOA inspections and in the South African case. In the former case they understood the technology of gas centrifuge cascades and heavy water reactor operations. Efforts to irreversibly dismantle weaponisation facilities and manage associated knowledge will likewise require these technical experts, even more so than in the case of the JCPOA. It is also unsurprising that the TPNW's only former nuclear-armed state, South Africa, has taken the lead in developing the Ban Treaty's nuclear weapons' elimination and disarmament verification provisions.[103]

Conclusion

Nuclear latency is a justifiably sensitive topic in multilateral nuclear diplomacy. Efforts to discuss its management and control frequently produce heated disagreements among representatives of different states. This is not unexpected, as the NPT, the TPNW, and many NWFZs permit States Parties to develop robust civilian nuclear energy capabilities. Mastery of the civilian nuclear fuel cycle does, however, move states closer to being able to develop nuclear weapons should their leaders opt to make that political decision. The resultant highly latent, or threshold, nuclear states will have little interest in reigning in their civilian nuclear energy programmes while other states maintain large arsenals of deliverable nuclear arms.

That point notwithstanding, future disarmed nuclear weapon states are not the only parties relevant to achieving and working hard to maintain an IND world. Latent states that have never produced a single nuclear weapon may actually share structural similarities with disarmed nuclear states. Each of these two types of highly latent nuclear states has a head start toward the bomb given its material, capital, and labour requirements. Our synthetic case discussed in this report offers some indications of the magnitude of these challenges. Controlling the hedge and eliminating potential pathways to the bomb is thus central to the idea of irreversibility. Thinking creatively about IND solutions and managing nuclear latency should be taking place now to support eventual multilateral disarmament processes, rather than down the road once the ranks of latent states have risen.

This report has provided evidence and analysis suggesting that uranium enrichment, plutonium reprocessing, and weaponisation knowledge all pose risks of upending a disarmed world. Yet, past experiences in the denuclearisation domain addressed specific problems and presented specific solutions. I showed in the preceding sections how all three types of these activities could manifest in a single case. It is this hypothetical synthetic case that provided the basis for my assessment.

While verification in an IND world will be costly and imperfect, by leveraging numerous interlocking layers of verification together, levels of risk will appreciably decrease. The two types of layers I focus on are well-known ways to strengthen the global nuclear nonproliferation regime and country-specific measures. The former are simply a matter of best practices and should be pursued regardless. The latter will entail dedicated political will and a commitment to allocating more extensive resources to monitoring and verification. Ultimately, eliminating pathways to the bomb is not just a scientific and technical problem. At the end of the day, the layered verification framework is premised on the idea that there may well be attempted non-compliance; it even expects this to occur. But there is a remarkably high probability of detecting and deterring militarily significant non-compliance.

[102] TPNW, Art. IV.

[103] Rebecca Davis Gibbons and Stephen Herzog, "The First TPNW Meeting and the Future of the Nuclear Ban Treaty", *Arms Control Today*, Vol. 52, No. 7 (2022), pp. 12–13, https://www.jstor.org/stable/27173075.

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Abstract

The concept of irreversibility in nuclear disarmament is gaining increasing attention in multilateral diplomacy, policy analysis, and scholarly research. Yet, continuous monitoring and verification of future disarmed nuclear states is insufficient for ensuring irreversibility. A nuclear-weapon-free world also will require careful attention to advanced civilian nuclear energy programmes. This report therefore lays out a framework called layered verification that is intended to eliminate pathways to weaponisation among highly latent nuclear states. The framework uses multiple interlocking international and country-specific non-proliferation approaches to reveal attempts to cross the nuclear threshold. Implementing layered verification will require considerable political will and financial costs. Nevertheless, it offers promise for detecting and deterring militarily significant non-compliance with disarmament commitments.

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