Research in Progress: Distributed Ledger Technology and Nuclear Safeguards

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Nuclear safeguards are a central pillar of international nuclear nonproliferation efforts. Teams of international inspectors—primarily, but not exclusively, from the International Atomic Energy Agency (IAEA)—routinely visit nuclear facilities worldwide to verify that no nuclear material has been diverted from civilian power plants to nuclear weapons efforts. Inspectors engage in material accounting, measuring nuclear materials that enter a facility and comparing those measurements with a facility's output. This task is complicated, however, by a number of factors, including routine changes to nuclear process lines, adversarial relationships with host countries, incentives to minimize the disruptions caused by inspectors while on site, and, of course, real efforts by governments to divert material for a bomb without alerting inspectors.

The structure of international nuclear safeguards seems a natural fit for distributed ledger technology (DLT). The primary task of inspectors is to maintain a kind of ledger, identifying nuclear inputs and outputs. The ability to securely and verifiably make changes to a distributed ledger offers a number of potential benefits to inspectors, to nations interested in making safeguards more effective, and to host countries looking to minimize the cost and effort of the safeguards regime. Like any new safeguards technology, however, there are substantial barriers to acceptance of DLT both by the IAEA and states that are subject to international inspection.

This research in progress memo discusses the potential benefits of DLT for nuclear safeguards, highlighting the prospects for adoption by the IAEA and by member states with different perspectives on the safeguards process.

IAEA Inspections and Distributed Ledger Technology

The IAEA is responsible for conducting safeguards inspections to verify the accuracy and completeness of state declarations about their civilian nuclear infrastructure. A typical inspection visit varies by the type of nuclear facility, but it might involve matching pipework to design documents provided by the state, confirming that spent nuclear fuel assemblies remain undisturbed in a spent fuel pond, or verifying that IAEA-installed locks and seals have not been tampered with.

The primary task of nuclear safeguards inspectors, however, is to ensure that no nuclear material has been diverted to a secret facility elsewhere, away from the watchful gaze of the international community. This task—material accounting—largely involves measuring the material that comes into the facility and comparing it to the material that leaves the facility.[1] Missing material is a red flag for potential diversion and calls for additional investigation. For inspectors on the ground at these facilities, material accounting means filling out a ledger (often a piece of paper on a clipboard, but sometimes on a laptop). Inputs go in one column, outputs in another, and these values largely cancel out at the end. The inspector's ledger is matched to one provided by the facility operator to confirm that no discrepancies exist.

This system is largely the same today as in the 1970s, when inspection procedures were first developed on a large scale after the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) thrust the IAEA into its new role verifying the non-military use of

[1] For far more detail on this process than anyone could really want, see International Atomic Energy Agency (2008) and International Atomic Energy Agency (2015).

nuclear technology. A number of observers and analysts have pushed to modernize these efforts over the years, calling at least for the provision of electronic material accounting records that could be accessed and verified by inspectors remotely, reducing the time and cost required to confirm the non-diversion of material from a nuclear facility.[2] Over the last several years, these calls for change have grown louder and more frequent, with analysts drawing particular attention to the application of distributed ledger technology to the case of nuclear safeguards.

DLT, the technological system underlying cryptocurrencies such as bitcoin, can be thought of as a database that is shared across a network of users. DLT allows changes to be made to this ledger in a way that is secure, verifiable, and tamper-evident (Vestergaard 2018).[3] While the distributed ledger that supports bitcoin and other cryptocurrencies must be publicly accessible, this is not a requirement of DLT systems generally. Many DLT applications in industry and finance limit access to a small group of trusted participants (Rauchs et al. 2018).

The Promise of DLT in Nuclear Safeguards

The adoption of DLT for nuclear safeguards offers a number of potential benefits to international safeguards inspectors and member states. First, a DLT safeguards system promises more rapid notification of discrepancies in material accounting (P. McBurney, C. Hobbs, and M Moran 2018; Vestergaard 2018; Vestergaard and Umayam 2020). At

[2] See, among many, Siegel, Steinbruner, and Gallagher (2014).

[3] The most well-known type of DLT is blockchain, but not all forms of DLT make use of blockchain. The more general term, DLT, is used in this memo. See Rauchs et al. (2018).

some safeguarded facilities, documentation necessary to verify the material balance is assembled and checked only periodically. Inspectors may have to work through a backlog of physical inventory listings and inventory change reports to calculate the material balance, by which time weeks or even months may have passed since nuclear material was diverted from a facility. DLT avoids this problem by allowing parties to update their nuclear material inventories in real time.[4]

More rapid detection of any material balance issue goes directly to a major security concern of nuclear facility operators and international inspectors—the risk of an insider threat (Vestergaard and Umayam 2020). Reducing the amount of time between diversion and detection has important implications for nuclear nonproliferation generally, but it also creates a more substantial deterrent for facility personnel who might otherwise be tempted to steal nuclear material. Insiders are most likely to try to divert very small amounts of material repeatedly over time, rather than a large amount all at once, to avoid detection. If DLT enables more rapid identification of missing material, this pathway to nuclear smuggling becomes riskier for the perpetrator and thus less likely.

DLT may provide better security for documentation of nuclear inventories and other sensitive information coming from safeguarded facilities. States have been reluctant to share information with the IAEA electronically for fear that it would be

[4] This is not so much a benefit of DLT itself as it is a benefit of the use of shared electronic systems for material accounting which can be updated by both the facility operator and IAEA inspectors. But one substantial barrier to implementing these shared systems is a lack of a durable security model that makes any changes to shared data transparent and verifiable. DLT addresses the latter problem.

vulnerable to leaking by the IAEA or unauthorized access by others. This concern applies in particular to sensitive commercial processes that might be revealed by sharing remote monitoring data or video feeds. DLT offers at least the possibility of addressing these concerns and making state parties more willing to share real-time information with the IAEA.

DLT also may make the safeguards process more efficient and less labor intensive. Part of the potential efficiency gain stems merely from moving paper records to electronic media and from sharing information between facilities and inspectors more frequently. But since one of the principal tasks of inspectors during an on-site visit is to collect data to verify the material balance of the facility, DLT and the real-time information sharing it facilities might allow inspectors to reduce the frequency of in-person inspections in some cases. This efficiency gain is potentially quite important: In-person inspections are extremely costly, both to the IAEA and to nuclear facility operators, who must shut down process lines and make a variety of accommodations to support inspector visits.[5]

Finally, it is at least possible to imagine some features of DLT being used to build trust between IAEA member states (Frazar et al. 2017). One possibility is the implementation of a consortium ledger system, in which copies of the ledger are distributed across participants, but the ability to make changes to the ledger are

[5] The prospect of less frequent on-site inspections of course has important implications for nuclear non-proliferation generally. No amount of electronic data sharing can completely replace the monitoring and deterrent against cheating provided by in-person visits of trained international inspectors.

concentrated among a smaller group. In this kind of arrangement, state parties might be able to independently verify that a particular state was complying with its nuclear safeguards requirements—in terms of timely information sharing with the IAEA—but would not have access to any sensitive data from that state's nuclear facilities, potentially increasing confidence that the safeguards system is functioning as intended.[6]

The IAEA and New Safeguards Technologies

Arrayed against these benefits are the usual barriers to adoption of new technologies by a large institution running on a tight budget. The cost of implementation is a substantial barrier, of course, coupled with any potential security risk—from malice or operator error—associated with moving to electronic record-keeping. And the inertia of established processes and procedures in large organizations may well play a role in the decision to adopt a new technology. The IAEA's track record, however, suggests that it will take steps to integrate new technologies into its safeguards efforts when the benefits of such technologies are evident.

The IAEA has not always rapidly embraced new technologies, but its adoption of new technologies over the years has clearly improved the Agency's ability to verify the non-diversion of nuclear material. Monitoring systems, for example, have seen substantial improvements. The IAEA in the 1970s monitored spent-fuel pools using a pair of cameras set to take a photograph every twenty minutes. Inspectors would attempt to review thousands of black-and-white images at every visit, looking for any sign that the

[6] Confidence in the efficacy of safeguards may be an important driver of the decisions of states to comply with their own safeguards requirements. See Kaplow (2013).

spent fuel had been moved. In the last 25 years, however, the IAEA has deployed more advanced unattended monitoring systems. Today's systems can capture radiation and other measurements as well as images, and in some cases are monitored remotely (Schanfein 2008). While the IAEA has long benefited from satellite imagery provided directly from member states, only in the last 20 years has it gained the capability to independently order and analyze commercial satellite imagery in support of safeguards goals (Chitumbo, Robb, and Hilliard 2002). Access to satellite imagery is particularly important to identifying suspected undeclared facilities that might merit further investigation (Ferguson and Norman 2010).

Environmental sampling techniques were introduced to IAEA safeguards in the mid-1990s, allowing IAEA inspectors to measure the isotopic composition of nuclear materials, potentially contradicting a state's declarations (Donohue 1998; Donohue, Deron, and Kuhn 1994). Environmental sampling played an important role in building the noncompliance case against Iran, for example. Agency inspectors in 2003 requested access to a suspected, but undeclared, centrifuge workshop. Iran eventually allowed inspections, but only after an attempt to decontaminate the facility—replacing the floor, repainting walls, and moving equipment to other locations. Still, environmental sampling there detected enriched uranium particles that could not be explained by Iran's existing declarations and led to Iran's acknowledgment later that year that it had indeed conducted undeclared centrifuge testing at the facility using nuclear material (Samore 2005).

New safeguards technologies, however, often require the consent of the state being inspected. Environmental sampling, for example, has been in widespread use as a safeguards tool thanks largely to pressure on states to adopt an Additional Protocol (AP) to their safeguards agreement. Beginning in 1997, as a response to the undeclared nuclear activities in Iraq unearthed after the first Gulf War, NPT member states were encouraged to bring the AP into force to provide the IAEA with broader access in verifying the completeness of state declarations. This includes the requirement to declare nuclear facilities and allow inspections there even when nuclear material is not present, and the wider use of environmental sampling to provide assurances that nuclear material has not been introduced at undeclared sites (Hirsch 2004).[7]

Absent a concerted pressure campaign akin to the push for widespread AP adoption, states are free to reject the use of any safeguards technology that was not part of their initial agreement with the IAEA. The path forward for such technologies thus depends on the particular incentives of the states being safeguarded; it is not enough to convince the IAEA that DLT is a good idea.

Three Types of Safeguarded States

For their part, states have very different incentive structures depending on their relationship with the IAEA and the broader nuclear nonproliferation regime. When it comes to their interactions with the IAEA, some states—particularly those with commercial nuclear facilities—are primarily interested in the *efficiency* of nuclear

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[7] On the importance of the Additional Protocol for limiting proliferation generally, see Schulte (2010).

safeguards. These states generally support the global safeguards system as an important tool in limiting nuclear nonproliferation, but they hope to minimize the impact of safeguards on commercial enterprises operating within their borders. For these states, adoption of DLT for nuclear safeguards makes sense. The technology's efficiency gains outweigh the initial start-up costs in technology and training, and the possibility of streamlining inspection visits looms large in this calculation. Two states in this category, Finland and Australia, have pilot programs in progress that are developing DLT systems that could be used by their respective nuclear regulatory agencies (Stimson Center 2020; Yu, Obbard, and Le 2018).

Another category includes states that have a more adversarial relationship with the IAEA and are less invested in the global nuclear nonproliferation regime. These states often see IAEA safeguards inspections as a mechanism for the international community to monitor or even limit their nuclear progress. States in this category frequently express concerns about the risk of commercial espionage enabled by inspector visits, and they take pains to limit inspector access as much as possible. Brazil offers one example of this tendency, at one point placing large barriers in front of the gas centrifuges at its Resende uranium enrichment facility so that IAEA inspectors would not be able to make off with its proprietary centrifuge technology (Squassoni and Fite 2005).[8]

For states in this second category, the primary concern is the *security* of nuclear safeguards, rather than their efficiency. These states may be less inclined to adopt DLT

[8] Some analysts argued that Brazil's concerns went beyond corporate espionage, as its centrifuges may have used technology acquired through black-market nuclear smuggling networks (Squassoni and Fite 2005).

because providing a real-time nuclear material inventory or other sensitive data provides an additional avenue by which this data could be viewed by unauthorized parties. While DLT offers a number of security benefits over other mechanisms for electronic data sharing, states may well feel more secure with the limited non-electronic access they currently provide. One countervailing factor, however, is the effect of DLT adoption on the pace of on-site visits by the IAEA. States in this category see on-site visits as a danger to the security of their facilities, and so may be willing to use DLT in exchange for commitments to reduce the frequency of in-person inspections.

A final category includes states with plans to divert material from safeguarded facilities for use in a secret nuclear weapons program, or those that wish to maintain the option to divert material in the future.[9] There probably are not many states in this category, but the entirety of the IAEA safeguards apparatus is focused on those few who would use their civilian facilities for military purposes. States in this category are more concerned about safeguards *effectiveness* than they are efficiency or security. For states that may seek to divert nuclear material, it makes sense to veto the adoption of any safeguards technology that makes the IAEA more likely to detect diversion. The risk that DLT will make safeguards more effective probably outweighs any efficiency or security argument. Even the prospect of fewer in-person inspections would be unlikely to redeem DLT in the eyes of such states. Iran, for example, fought for years to prevent the IAEA from installing cameras with remote monitoring capabilities in their nuclear facilities,

[9] Nuclear hedging is the strategy of building up dual-use nuclear capabilities to maintain the option to seek weapons if necessary. See the contributions in Pilat (2019).

preferring to have inspectors visit in person to review the photos along with other data (Heinrich 2009).

DLT and Nonproliferation

These three categories of states—primarily concerned with efficiency, security, and effectiveness, respectively—help to clarify the potential impact of DLT on nuclear nonproliferation outcomes. The efficiency case for DLT is quite strong; the prospect of real-time sharing of nuclear inventory data and faster notification of discrepancies in the material balance are likely to convince a substantial number of states to adopt DLT for safeguards. But these states tend to present few nonproliferation concerns. For the second category of states most concerned about security, adoption of DLT is possible, although it may require a concerted effort to demonstrate the security benefits of a distributed data-sharing model.

It seems unlikely, however, that states in the final category—those most concerned that DLT will help the IAEA detect an effort to divert nuclear material—can be convinced to adopt the technology, absent significant pressure from the international community. Such pressure was effective in the case of the push for AP adoption starting in the late 1990s. The AP, however, involved a substantial expansion of the areas under the IAEA's purview. It demonstrably made the IAEA more effective at identifying undeclared nuclear facilities. DLT, while it offers substantial benefits, seems far less likely generate the political will on the part of the international community that would be required to pressure hold-out states to come on board.

Future Research

This memo is a first step in describing the potential benefits of DLT in nuclear safeguards and the potential for adoption by both the IAEA and member states. In future work, we hope to expand on this work in at least three ways. First, we plan to analyze in more detail the effects of DLT on safeguards effectiveness, efficiency, and security, with particular attention to the experiences of the two pilot DLT safeguards efforts that are currently under development. Second, we plan to expand our discussion of the history of technology adoption in the IAEA, drawing more direct parallels with the potential use of DLT by the Agency. Third, in future work, we plan to be more systematic in our treatment of the different categories of member states and their likelihood of DLT adoption. We also will investigate the circumstances surrounding state agreements to adopt technologies such as remote monitoring cameras, environmental sampling, and electronic data sharing.

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