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Evaluating Member State Acceptance of Blockchain for Nuclear Safeguards

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Executive Summary

Distributed ledger technology (DLT) combines technologies and computing concepts (including cryptography, peer-to-peer protocols, hashing, and distributed consensus algorithms) to allow a network of participants to share and validate data across a tamper-evident ledger. The linkage and replication of data among participants, coupled with a consensus process, form an authoritative ledger accessible to all participants. Governments and commercial industries have adapted the technology for various applications beyond cryptocurrencies, from tracking pharmaceuticals to digitizing and securing global shipping data.[1] Recognizing the potential for DLT to disrupt existing practices for sharing information and conducting online transactions, the Stimson Center, the Stanley Center for Peace and Security, and the Pacific Northwest National Laboratory (PNNL) independently initiated several research projects in 2017 that explored the technology's implications for the International Atomic Energy Agency (IAEA) safeguards system.[2] As these projects progressed, questions emerged whether nontechnical hurdles such as legal and political barriers and deployment costs would be sufficiently high to hinder deployment.

To begin answering questions about the nontechnical barriers to deployment, the aforementioned organizations, with partial sponsorship from the National Nuclear Security Administration (NNSA), coorganized a workshop in June 2019 that examined stakeholder desirability for using DLT for safeguards purposes. The two-day event conducted in Vienna, Austria, included a primer on how DLT functions, a description of commercial applications of DLT, and discussion on potential deployment challenges and opportunities as perceived by nuclear operators, state authorities, and the IAEA. Surveys at the beginning and end of the workshop documented whether and how participants' perceptions shifted. Discussions were conducted under the Chatham House Rule, that is, without attribution. The workshop included 15 participants from nine IAEA member states, representing nuclear operators, state authorities, and national missions. The workshop also included participants from blockchain companies, research institutions, and international organizations.

This report summarizes the observations from the workshop and highlights several key findings from the workshop.

Key Findings

- DLT presents an evolution in computer science while offering new functionalities for safeguards.
- DLT acceptance will depend, in part, on educating member states about how the technology works. Participants' views of DLT's ability to improve operational efficiencies, data security, and confidentiality of safeguards data improved at all levels (operator, state, and IAEA) through the workshop. Education with member states will be particularly important as DLT continues to evolve.
- DLT offers something above and beyond existing information management systems at the IAEA (e.g., interoperability among systems, frontloading inspection efforts) without replacing the important regulatory function of performing physical verification of nuclear inventories.
- DLT platforms would not change what safeguards information is reported or undermine the extent to which it is protected from manipulation or theft, two of the most politically charged issues for the international safeguards community.
- The IAEA—with its limited budget and limited mandate on technology research—is not best positioned to drive investment in DLT systems for safeguards. Although interest among workshop participants in having operators invest in DLT research was relatively low, 76 percent of participants indicated that state authorities should lead the way, possibly because it would be cheaper, less political, and more "exploratory" if a state takes the first leap.
- While stakeholders perceived legal requirements for adoption to be manageable, political challenges at the IAEA were likely to hinder the technology's deployment.

This report aims to inform member states and the IAEA about the challenges and opportunities associated with deploying DLT for safeguards purposes. It also explores potential user requirements that should be considered if stakeholders decide to move forward with designing a DLT for safeguards verification and analysis.

Introduction

Bitcoin is "the first blockchain."[3] It is a prime example of the open blockchain, which allows anyone with an Internet connection to participate in a borderless system for financial payments. From its beginning, Bitcoin was closely linked with the blockchain, becoming synonymous with the generic blockchain in popular culture—yet the two are distinct. Bitcoin is a cryptocurrency whereas the blockchain is a distributed ledger that facilitates Bitcoin transactions. It enables an open, peer-to-peer system to authenticate transactions or a "chain of transaction blocks," removing the need for intermediaries or banks.[4] The Bitcoin blockchain is the first mainstream example of a broad class of distributed ledger technology (DLT) that combine technologies and computing concepts (including cryptography, peer-to-peer protocols, hashing, and distributed consensus algorithms) to allow a network of participants to share and validate data across a tamper-evident ledger. In all distributed ledgers, "Parties post transactions pseudonymously, meaning their identities are protected but details about the transaction remain transparent. Computer programs…process the…transactions taking place on the ledger based on a secure system rooted in cryptography."[5] The linkage and replication of data among participants, coupled with a consensus process, form an authoritative ledger accessible to all participants.

DLT Functionality

- A distributed ledger is a decentralized database that stores a registry of assets and transactions across a peer-to-peer network.
- The ledger is a public registry of who owns what and who transacts what.
- The transactions are secured through cryptography.
- Over time that transaction history gets locked into blocks of data that are cryptographically linked and made secure.
- This secure linking creates an immutable record of transactions that is impossible to forge.
- It allows users to store digital assets—cryptocurrency, a title, a certificate, or a contract.

Governments and commercial industries have adapted blockchain technology for various applications beyond cryptocurrencies, such as for tracking pharmaceuticals[6] and diamonds[7] or digitizing and securing global shipping data.[8] Each application and ecosystem for which the ledger is being developed drives the ledger's design features, such as who is allowed to access the ledger under what conditions (permissions) and what types of information are shared. Participation is restricted to preapproved nodes on the network, across multiple organizations (commonly referred to as consortium blockchains), or internally within one organization (private blockchains). These permissioned platforms enable collaboration among parties, allowing the entire network to derive benefits from interoperability in process automation and data traceability.[9]

The rapid evolution of DLT use cases has led to market fragmentation and a jumble of terms used interchangeably to describe the same bucket of technologies, including "blockchain," "blockchain technologies," or "DLT." This report uses "DLT" as the overarching term to describe the weaving of underlying technology, such as cryptography, peer-to-peer protocols, hashing, and distributed consensus algorithms, and their various applications.

Research to Date on DLT and Nuclear Safeguards

Recognizing DLT's potential to disrupt existing practices for information sharing and online transactions, the Stimson Center, the Stanley Center for Peace and Security, and the Pacific Northwest National Laboratory (PNNL) independently initiated projects to explore the implications for national and international security. PNNL initiated a study in 2017 with sponsorship from the Office of Nonproliferation and Arms Control at the National Nuclear Security Administration (NNSA) to explore the potential blockchain technology applications to international safeguards.[10] As part of that effort, PNNL clarified key terms to construct a methodology for evaluating different use cases for blockchain technology. In 2018, PNNL produced a follow-on study that applied the methodology to different safeguards use cases involving digital transactions. That study highlighted transit matching and uranium hexafluoride (UF6) cylinder tracking as two use cases for deploying DLT.[11] In 2019, PNNL began designing a prototype ledger focused on transit matching.

In 2018, the Stimson Center and the Stanley Center for Peace and Security cohosted a series of workshops assessing the potential of DLT for safeguards with technologists and stakeholders from the International Atomic Energy Agency (IAEA), its member states, and various research institutions. These workshops informed an exploratory study on DLT's potential utility for managing safeguards information at the international, national, and facility levels. The study identified areas where a DLT platform could provide advantages for greater efficiencies and data security, such as IAEA transit matching, tracking the supply chain and safeguards obligations within a national system (state system of accounting for and control of nuclear material, or SSAC), and long-term information management at deep geological repositories.[12] The Stimson Center currently has two other projects underway: an exploratory study on DLT applications for nuclear security, funded by the NNSA, and a DLT prototype to be developed for the Radiation and Nuclear Safety Authority (STUK) in Finland. The STUK prototype, developed in partnership with the University of New South Wales, will be the first test of a DLT platform for a national system of nuclear material accounting.

These activities help address significant questions regarding DLT's suitability for safeguards and other nuclear security applications. However, there is a research gap on whether or how member states might accept DLT for these purposes. Significant questions remain regarding nontechnical hurdles such as legal and political barriers and whether deployment costs, which might be carried by member states, would be so high as to hinder deployment. Without clear member state interest in using DLT for nuclear safeguards, the IAEA is unlikely to impose the technology on them. To date, the IAEA has expressed interest in simply monitoring the technology's evolution in its long-term research and development plan[13] and in highlighted discussions at the 2017 Emerging Technology Workshop and 2018 Safeguards Symposium.

To address questions surrounding member state acceptance, the Stimson Center, the Stanley Center, and PNNL conducted a joint workshop in June 2019 in Vienna, Austria, to document member state perceptions about the desirability of deploying a distributed ledger platform for safeguards purposes. The two-day event included a primer on how DLT functions, a description of commercial DLT applications, and discussion on potential deployment challenges and opportunities as perceived by nuclear operators, state authorities, and the IAEA. Surveys at the beginning and end of the workshop documented whether and how perceptions shifted. Discussions were conducted under the Chatham House Rule. The workshop included 15 participants from nine member states, representing nuclear operators, state authorities, and permanent missions to international organizations in Vienna. The workshop also included participants from private blockchain companies, research institutions, and international organizations.

This report summarizes the key findings and observations from the meeting. The report aims to inform the IAEA and member states about the challenges and opportunities associated with deploying DLT for safeguards purposes and any potential user requirements that should be considered if stakeholders decide to design or develop a DLT for safeguards verification and analysis.

The remainder of the report discusses and compares the participant survey results to the assumptions organizers held prior to the workshop. It reviews important points raised to move research beyond existing perceptions and misperceptions and establish expectations for future deployment. It focuses on the perceived incentives and challenges for DLT deployment and offers future design considerations.

Member State Perceptions

The IAEA has a stated goal of using new technologies to improve safeguards efficiencies and effectiveness. According to the IAEA's medium-term strategy, "The Agency will utilize its modernized IT system to optimize its work and disseminate information within the Department of Safeguards in a timely and secure manner and keep the system up to date by identifying and adapting to new and emerging technologies."[14] Yet introducing new technologies for safeguards can be challenging and time consuming. Each technology under consideration must undergo extensive testing and evaluation before it can be approved for safeguards use. For example, the IAEA took approximately five years to develop, test, and deploy two commonly used surveillance systems—the Digital Cherenkov Viewing Device and the Electro-Optical Sealing System. Introducing a DLT safeguards platform would face a similar rigorous evaluation by the IAEA and its member states. Due to the disruptive nature of DLT, and the variety of technical, legal, and political challenges associated with its deployment, it is possible its acceptance as a safeguards tool could take almost a decade.

Legal Barriers

The legal barriers might not be insurmountable—but the IAEA political barriers may be more challenging to manage.

In order to make sense of the variety of issues influencing member state perceptions, workshop organizers entered the event with a set of baseline assumptions. The survey conducted before and after the workshop was designed, in part, to determine the extent to which these assumptions held true, while workshop discussions were intended to bring out some of the nuances driving member state perceptions. As discussed in this section, survey results reinforced some key assumptions while rejecting others.

Assumption 1: Legal and Political Challenges to Deployment Will Be High

Promising technologies often fail to succeed because of nontechnical barriers to deployment. For any technology being considered for safeguards purposes, one of the first questions is whether the well-established legal system (comprising an international treaty, national laws and regulations, safeguards agreements, operator licenses, facility attachments, and subsidiary arrangements) will preclude its use. Workshop participants concluded that existing legal agreements between the IAEA and member states do not preclude future DLT deployment.

Paragraph 6 of the Comprehensive Safeguards Agreement (INFCIRC/153)[15] states that the IAEA "shall take full account of technological developments in the field of safeguards…to ensure optimum cost-effectiveness." This obligation suggests that the IAEA has a mandate to consider new technologies such as DLT that could help with effective and efficient safeguards implementation. At the same time, INFCIRC/153 does not impose a similar obligation on states to leverage technologies for safeguards purposes. INFCIRC 153 also does not explicitly require states to submit nuclear material accounting information electronically. Consequently, states have been slow to leverage the newest technologies for safeguards. For example, many states have passed laws that prevent electronic submissions due to security concerns. As a result, some states still provide safeguards reports by flash drive, CD, or paper format.[16]

The workshop raised other considerations for political acceptance. Paragraph 8 of INFCIRC/153 states that sensitive design information "would not have to be physically transmitted to the Agency provided it remained available for further examination by the Agency on premises." This means that existing safeguards agreements might allow use of an advanced technology such as DLT to support safeguards activities, but how much and what type of safeguards information can be shared on the ledger without violating confidentiality obligations is a political question.

During two days of workshop discussions, participants concluded that INFCIRC/153 does not preclude the use of emerging technologies for safeguards reporting. Participants focused instead on how associated political barriers can present significant challenges to universal deployment. Ultimately, they recognized the political requirements for adoption by the SSAC and operator were manageable, but IAEA political requirements were more challenging to manage.

In tables 1–5 and 7, "positive" includes survey responses of "agree" and "somewhat agree." "Negative" includes survey responses of "somewhat disagree" and "disagree."

Assumption 2: DLT Acceptance Will Require Revolutionary Change

The collection, management, and analysis of safeguards information submitted by states and IAEA inspectors are critical functions for IAEA function. According to the IAEA, "From 2010–2015, the number of States with Additional Protocols increased by 22%, the number of Nuclear Material Accounting Reports increased by 20%, and the amount of nuclear material under safeguards increased by 17%."[17] Between 1983 and 2019, the number of incoming reports submitted to the IAEA annually increased from 16,500 to approximately 1 million.[18]

For years, this information sat on several disjointed databases, making it difficult to access and analyze. Recognizing an increasingly urgent need to improve the efficiency of its information management and analysis capabilities, the IAEA launched the Modernization of Safeguards Information Technology project (MOSAIC) to improve interaction between the IAEA and its member states and enhance collaboration among IAEA inspectors and safeguards staff. Launched in 2015, MOSAIC was developed in five years at the cost of 41 million euros.[19]

Feedback from previous workshops on the DLT for safeguards indicated that the IAEA is cautious about making investments in new technologies, based on its investment in MOSAIC. In addition to a new technology being thoroughly tested, the IAEA and member states must mutually agree that the technology's deployment will bring significant value to safeguards activities. "Merely freeing resources from one activity so they can be applied to another" is an insufficient reason for investing in DLT research and deployment.[20] Early misperceptions about DLT focused on whether the technology might significantly alter the IAEA's central role, potentially replacing it altogether, like banks being replaced as the central authority responsible for managing

Evolutionary Change

DLT offers a paradigm shift to safeguards information management, even though the technology itself is evolutionary.

Table 1: The legal requirements adoption of a DLT platform seem manageable.
Responses before and after workshop, segmented by end user.

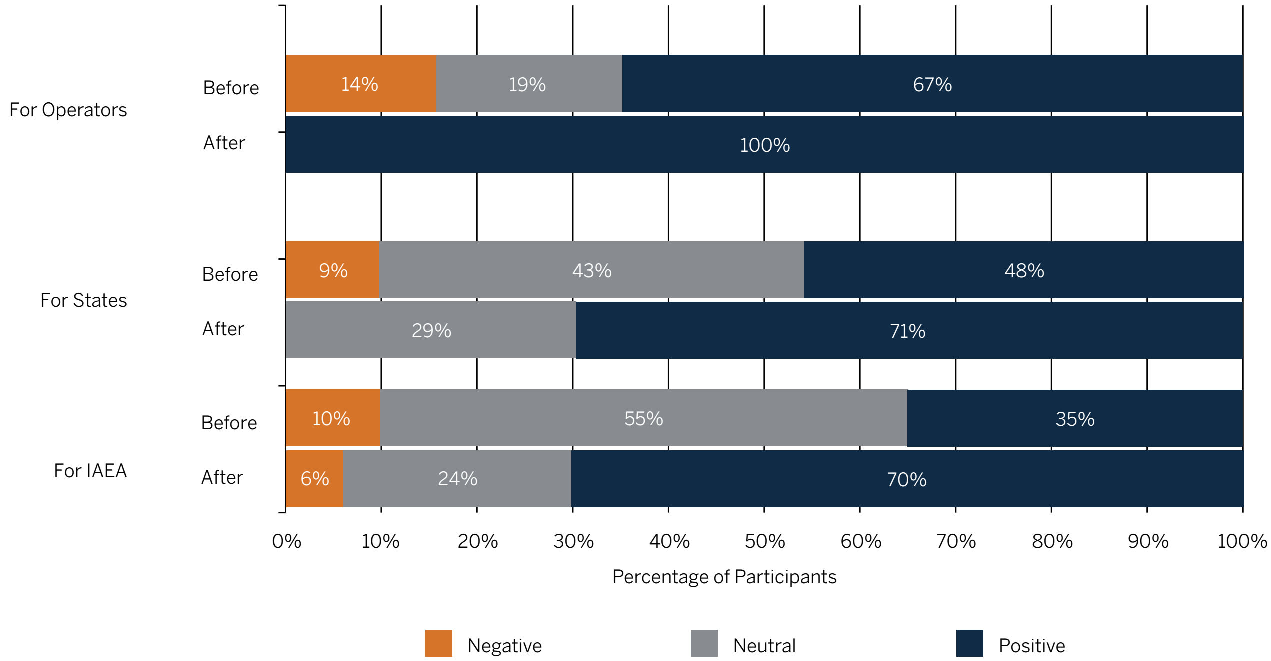
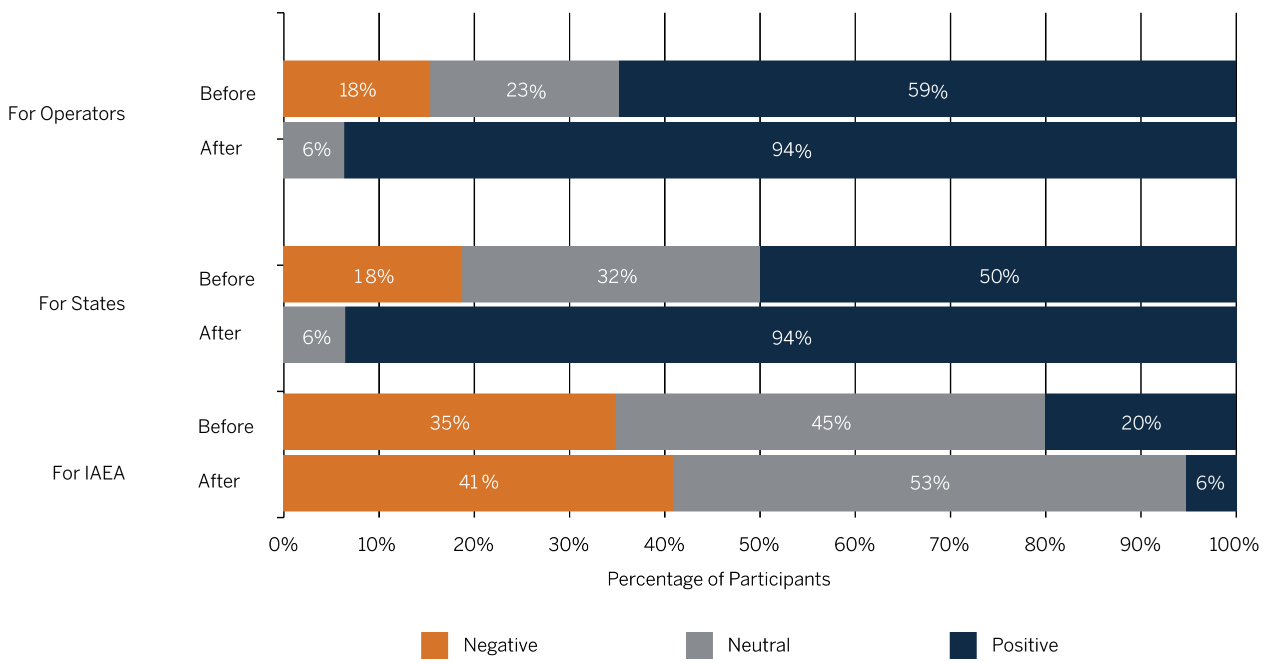


Table 2: The political requirements for adoption of a DLT platform seem manageable.
Responses before and after workshop, segmented by end user.



cryptocurrencies. In fact, as participants discussed during the workshop, DLT offers something above and beyond MOSAIC without replacing the IAEA's central regulatory function and the need for physical verification.

Through education and socialization about the technology's functionality, participants in the June 2019 workshop learned about DLT's ability to improve workflow efficiency, system interoperability, data analytics, data security, and confidentiality. They gained a better appreciation for how the DLT data structure facilitates automated workflows and rapid transaction processing times (average of 5–10 minutes) without undermining data integrity, something that MOSAIC does not offer. Accordingly, participants learned through discussion that DLT presents an evolution in computer science while offering new functionalities for safeguards.

The survey results reflected this shift in perception about DLT's ability to provide benefits to the safeguards system, particularly to improve operational efficiencies, data security, and confidentiality of safeguards data. As shown in table 3, participant belief that DLT offers benefits to safeguards increased from 45 percent to 100 percent. Table 4, table 5, and table 6 indicate there was a 10–30-percent increase in positive perceptions about DLT's ability to specifically improve efficiency in the IAEA, state, and operator levels while neutral responses increased by the same amount. These results suggest that DLT acceptance will depend, in part, on educating member states about how the technology works, particularly as it continues to evolve, and how it would be applied in safeguards- and non-safeguards-use cases.

Assumption 3: DLT Investment Will Be Driven by Member States

To date, a small community of researchers has explored DLT's potential applicability for national and international security (e.g., safeguards, nuclear security, export controls).[21] These researchers come from governments, operators, universities, and nongovernmental organizations. Early research suggests that the IAEA, with its limited budget and limited mandate on technology research, is not best positioned to drive investment in DLT. The IAEA has expressed interest in monitoring the discussion but has not yet invested funds into member state support program activities to explore or develop a ledger for safeguards purposes. When asked who should pay for DLT research, 76 percent of workshop participants initially identified the IAEA as the best positioned to invest the resources. By the end of the two days, 76 percent of participants indicated that state authorities should lead the way, possibly because it would be cheaper, less political, and more "exploratory" if a state takes the first leap.

Interest in having operators invest in DLT research was relatively low, a perspective that did not change over the course of the workshop. The percentage of those believing the benefits of research and deployment outweigh the costs increased slightly. Survey results reinforced the assumption that member states would likely bear the costs for DLT deployment.

Reality of Reporting

DLT platforms do not change what information is reported or undermine the extent to which it is protected from manipulation or theft—two of the most politically charged issues discussed by the international safeguards community.

Drivers

The IAEA, with its limited budget and limited mandate on technology research, is not best positioned to drive investment in DLT.

Table 3: DLT offers significant benefits to the safeguards system.
Responses before and after workshop.

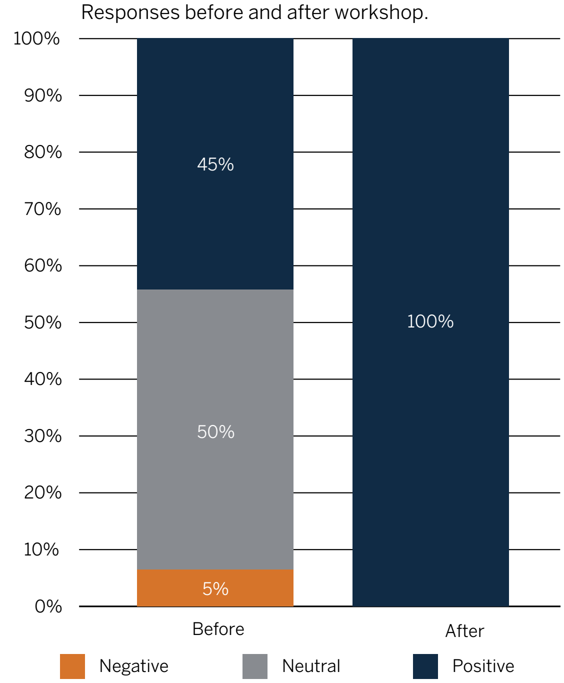


Table 4: Using a DLT platform for safeguards could improve efficiency.
Responses before and after workshop, segmented by end user.

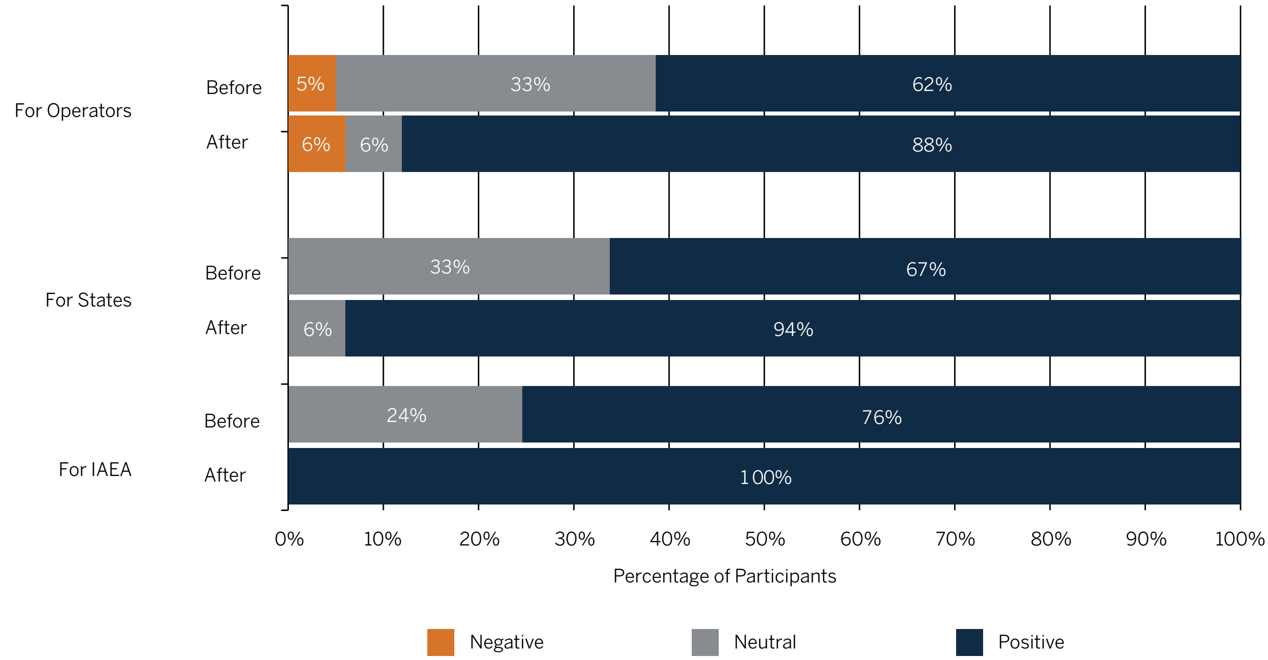


Table 5: Using a DLT platform to transmit safeguards information could improve data security and confidentiality.
Responses before and after workshop, segmented by end user.

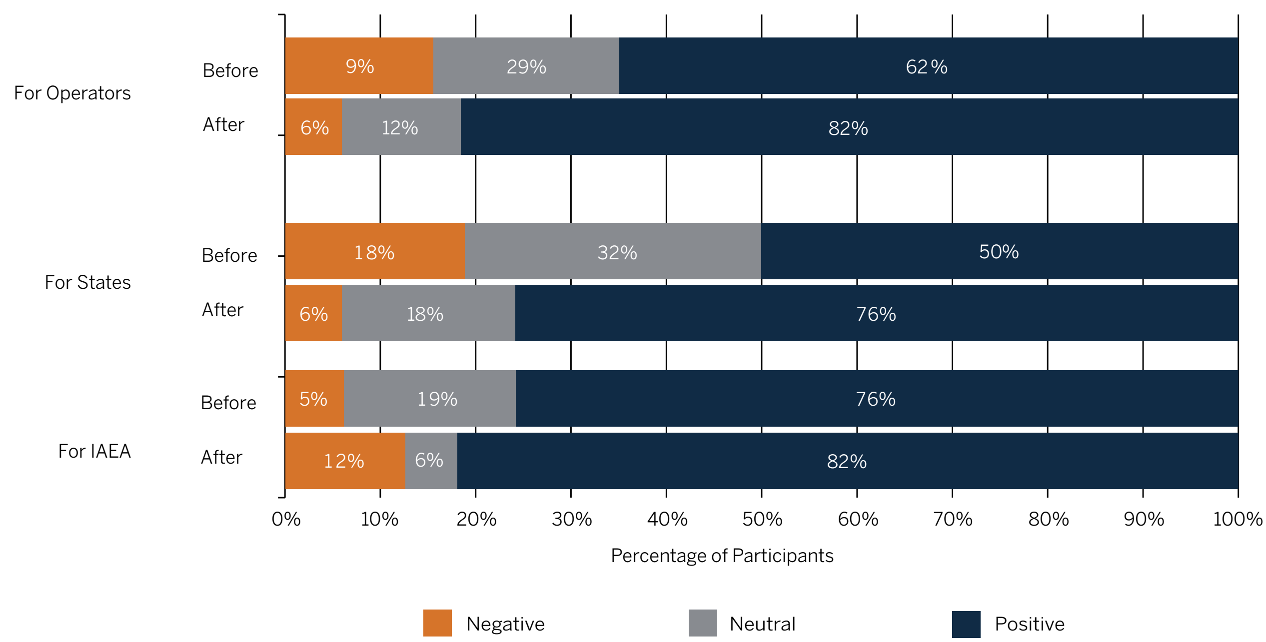
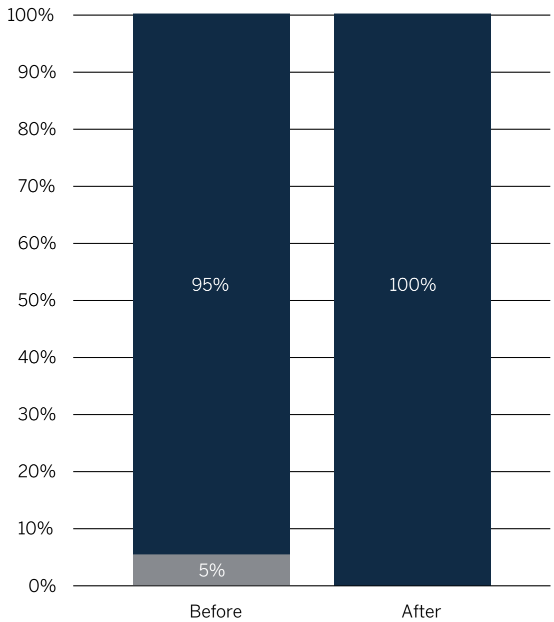


Table 6: Using a DLT platform to store safeguards information could improve data integrity and tracability.

Responses before and after workshop.



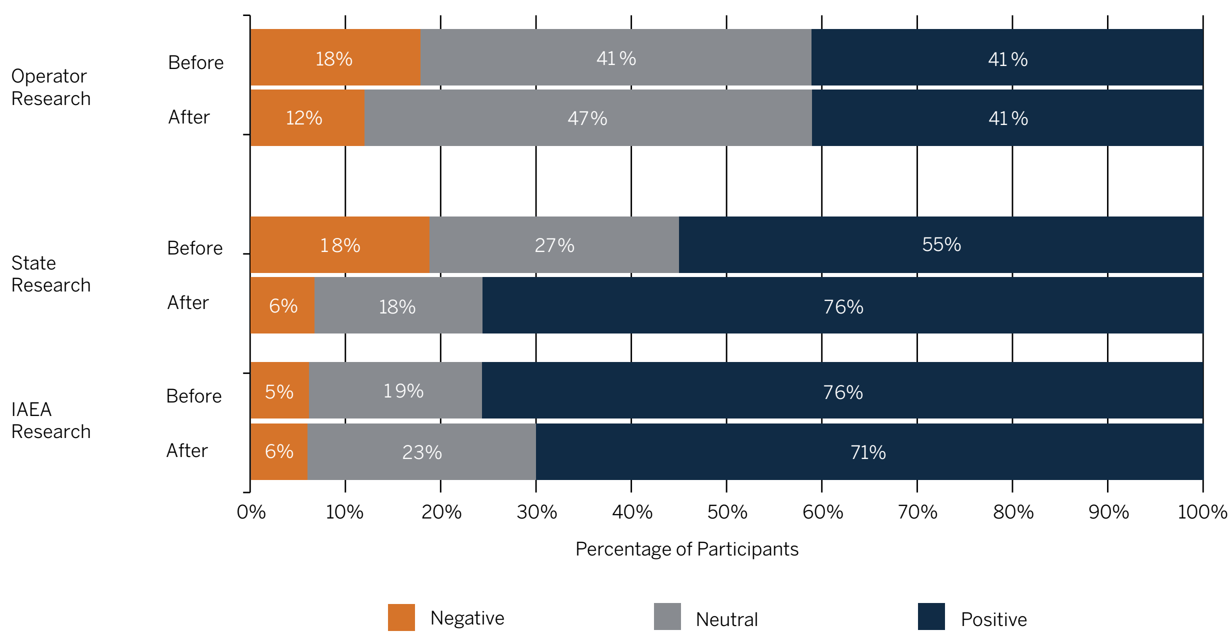
From Perceptions to Reality

The survey results on member state perceptions highlight important issues for further discussion on the feasibility and desirability of deploying DLT platforms for safeguards use.

The participant survey results indicate that despite its reputation as a disruptive technology, when applied to various use cases (including safeguards use cases), permissioned DLT platforms may facilitate a less disruptive, evolutionary change. First, workshop participants recognized that DLT platforms will not replace the IAEA as an independent verification body. IAEA inspectors would continue to visit facilities to perform inspections and verify physical inventories against information recorded in the ledger. Second, if a DLT platform were integrated into existing systems—as participants suggested—and used to provide real-time reporting of nuclear material inventories, few believe that DLT platforms would force states to report additional safeguards information beyond what is already required by safeguards agreements. Third, although states and the IAEA express deep and legitimate concern about posting highly sensitive safeguards information on DLT platforms, the multiple layers of encryption and cryptography inherent in the blockchain data structure provide at least the same level of security offered by existing encryption technologies. Finally, participants did not anticipate that safeguards agreements would need to be updated, as states will continue to meet their obligations. In short, the survey indicated that these important political concerns were assuaged.

Table 7: IAEA, state, or operator research investments into a DLT platform would be an effective use of resources.

Responses before and after workshop, segmented by end user.



With an evolutionary application of DLT for safeguards, the potential outcomes could be significant in terms of improving the timeliness for detecting diversion and mitigating some of the politics inherent in the noncompliance process. For example, rather than wait 30 to 60 days after a change has occurred to receive an inventory change report, inspectors and analysts can monitor changes, and identify discrepancies, in real time.[22] This capability could inform where the IAEA conducts Complementary Access under the Additional Protocol or improve the effectiveness of routine inspection plans, which could also improve the IAEA's ability to detect undeclared processing of nuclear material. In the process, a tamper-evident, transparent ledger reinforces IAEA confidence in the information being provided, even as adjustments and corrections are appended to the ledger. Such improvement in analytical efficiency and trust in state-provided information could also transform how the IAEA ultimately reviews and prepares information for closer scrutiny by the board of governors during periods of political debate.

For now, the IAEA continues to monitor the trajectory of this technology along with member state perceptions about its use as a safeguards accounting tool. Discussions such as those conducted at the June workshop continue to raise a number of questions that will need to be addressed before deploying such technology for safeguards use. To that end, the next sections discuss deployment incentives and user requirements from each stakeholder perspective.

Deployment Incentives

Based on workshop discussions, member states recognize and desire the increase in operational efficiency that DLT platforms could bring to international safeguards. Workshop participants from member states demonstrated general agreement that the ability to track nuclear and nonnuclear items, along with associated information and movements in a single, tamper-evident, time-stamped database would likely decrease operator and inspector burden while maintaining confidence in safeguards conclusions. Ultimately, the major stakeholders—the IAEA, state authorities, and operators—held different perspectives about DLT's benefits and challenges.

IAEA Deployment Incentives

DLT platforms offer IAEA inspectors a streamlined, consistent, and auditable transaction ledger, which reinforces the continuity of knowledge at the facility and provides real-time insights into the location of all safeguards-reportable materials at the facility. An improved information-management and data-analytic capability allows the IAEA to plan better for on-site inspections, knowing in advance what types of measurements and instruments need to be taken.

This capability is attractive for several reasons:

- It could reduce the burden on the IAEA and operators by enabling the IAEA to develop a more targeted, effective, and efficient inspection plan, and supporting the implementation of integrated safeguards in a state.
- It could improve timeliness in detecting diversion. A diversion scenario conducted during a trial study comparing Australia's current Nuclear Material Balance Tracking System to one that runs on a blockchain-based platform underscored how diversion and collusion between a state regulator and a license holder could be "easily noticed by the IAEA."[23]
- It would allow for an inspector, prior to an onsite inspection, to verify the consistency between operator records and state reports submitted to IAEA headquarters as they would be identical on the ledger. This could potentially save 50% (or more) of an inspector's time at a facility (depending on the facility type) given that book inspections can be a large fraction of total inspection effort.
- If the DLT platform could be integrated into existing databases at the IAEA,[24] the IAEA would acquire a new capability to capture and inextricably link source documentation with inventory data, thereby replacing a function currently performed by hand. It is important to note that the integration of these databases would have to be voluntary, as there is no legal basis for such integration in INFCIRC/153. There is a hard line drawn between operator records and state reports, and deployment of DLT in this way would not just blur the line but completely erase it. If the IAEA decided to integrate the systems, it could see benefits, such as an immediate provision of near-real-time accounting information to the IAEA. There could be a drastic reduction in the amount of time taken to provide official accounting reports to the IAEA, and the IAEA would be able to provide immediate feedback about the quality of the information reported.

State Authority Deployment Incentives

The state authority perspective was similar in many ways to the IAEA perspective. In states with large, complex fuel cycles, a DLT platform could increase uniformity of facility information across the state, which would increase the authority's situational awareness and enable it to respond to IAEA questions more effectively and efficiently. Authorities expressed strong interest in the potential for DLT platforms to frontload reconciliation within SSACs before submission to the IAEA. They also saw benefits in how DLT enables data analytics to identify patterns—an important function as the agency moves toward focusing on a state's nuclear activities as a whole.

State authorities also are engaged in international nuclear commerce that involves a range of obligations and reporting subject to various bilateral nuclear cooperation agreements (NCAs). Several state authorities require NCAs as a prerequisite for the import and export of nuclear materials and technology to provide additional assurances of the peaceful uses of nuclear technology. NCAs include information-sharing measures to track material, attaching reporting obligations or "flags" to material as it moves through the global nuclear fuel cycle. These obligations begin from the export of uranium ore concentrates, then apply to material reprocessed or stored as nuclear waste and to plutonium in the spent fuel or recovered from it. This has led to a system of multiple flagging, where obligations from multiple suppliers can apply to the same item as it is processed in different countries.

NCAs also allow for "flag swaps," whereby "operators with uranium originating from one supplier [can] relabel the material under the nationality of another to minimize transport costs, ensure timeliness of product availability at contract-specified quantities, meet unexpected demand requirements, and optimize inventories."[25] Swaps are essentially book transfers used when a physical transfer would be allowed, but the actual physical transfer can be avoided by "swapping" materials at facilities. Simple in principle, flag swaps switch safeguards obligations and are therefore subject to bilateral treaty requirements and must follow a system of reporting, procedures, and prior approval by national authorities to ensure swaps do not weaken the nonproliferation regime.[26]

Accordingly, NCAs add another layer of complexity to safeguards information management by SSACs. DLT solutions could streamline accounting subject to specific NCAs while also benefiting the ability of states—and the IAEA—to transit match nuclear trade.[27] This, in turn, could streamline the process for export controls for nuclear (and other) materials and provide greater assurances in the traceability and integrity of the nuclear supply chain within and across national authorities.

Given states' international, regional, and bilateral safeguards reporting requirements, DLT platforms offer SSACs interoperability across facilities on transactions not just undertaken within the state but also in tracking flagged material moving across and within countries. This interoperability allows for greater efficiencies in accountancy systems and data analytics while providing users a secure, trusted platform.

Operator Deployment Incentives

From the operator perspective, DLT introduces opportunities to improve operational efficiency while augmenting safety and security at the facility. For example, a DLT platform could be used to track nuclear material, nonnuclear items, and process-related information, such as full and empty cylinders, casks, and canisters; transportation records; shipper-receiver records; personnel access records; and crane-movement records. Meanwhile, the ability to store instrument calibration records, measurement samples, and environmental swipe sample data on a tamper-evident ledger improves auditability and traceability. In countries with limited nuclear material, DLT could still enable transparent collaboration among regional partners exchanging radiological sources for well logging or medical purposes. Record accuracy is particularly critical during emergencies or instances when nuclear material goes missing or is discovered out of regulatory control.

Many operators (and regulators) at the workshop expressed a vision for the nuclear industry to have a single electronic data portal fed by operators that is validated by inspectorates and serves as the authoritative ledger for safeguards data and other purposes (such as export controls). In this scenario, one electronic data portal would contain information useful to different regulators within a state (including safety, environmental, safeguards, and export controls), regional authorities (such as Euratom), and the IAEA. Different regulators would then be permissioned to access data on the ledger as required by law. Participants in the workshop recognized that this would require intensive cooperation between the IAEA and regional and national authorities). They also recognized that attaining such cooperation would be a major challenge. However, if cooperation were not achieved, then operators saw limited justification for bigger investments by the industry for a DLT solution.

While operators expressed interest in the efficiencies to be gained from a single electronic data portal, they expressed caution when discussing the potential for including real-time reporting capabilities on a ledger. For many operators, reporting is required by the regulator once a month. The reporting system and operational procedures are therefore designed for monthly reporting to allow validation and reconciliation before submission. A private DLT platform within a company/facility could still track real-time reporting as per company policy, but posting reconciled data to a separate, shared consortium DLT platform involving the IAEA or regional authority would take place monthly.

For aggregate accounting, a consortium of DLT platforms for reporting obligations under NCAs could further streamline data and obligations accounting. States and their facilities are responsible for reporting on prior consent/approval constraints, notifications, and requirements, including for obligation swaps and exchanges.[28] In following a country's "flag" (i.e., obligated nuclear material as it moves through the nuclear fuel cycle), NCAs allow for the principle of equivalency/fungibility and proportionality (i.e., uranium atoms are equal by nature, if the same isotope). The equivalency principle provides that when obligated nuclear material loses its distinct identity due to process characteristics (i.e., mixing), an equivalent quantity of the processed material is designated as obligated. These quantities are derived from calculation, measurement, or operating plant parameters. Proportionality occurs when obligated nuclear material is mixed with other nuclear material and subsequently processed or irradiated, then a corresponding proportion of the resulting nuclear material is regarded as obligated. States and operators would need to discuss how measurements and calculations can be standardized to ensure uniformity and consistency across a consortium platform.

While efficiency is a primary deployment incentive, participants also recognized that DLT could improve transparency and consistency in reporting. Greater transparency enables operators and states to demonstrate compliance and potentially address inspector questions more quickly and accurately. Participants also expressed concern about protecting proprietary information but agreed that information would not have to be registered on a DLT platform.

User Requirements

In addition to understanding incentives for states, operators, and regional/international safeguards authorities to employ DLT, it is also useful to consider what such deployment might look. DLT platforms would vary in architecture and permissions, whether private (within one company) or consortium (across multiple organizations). At this stage of DLT research for safeguards information management, detailed user requirements have not been developed. However, based on past experiences in updating SSAC databases, workshop participants articulated a few user requirements to consider:

Close the gap: To generate DLT systems that address gaps and inefficiencies, platforms need to be flexible enough to anticipate changes (whether regulatory or operational) and require intuitive interfaces to facilitate access and use. To ensure operators and regulators utilize the platform, it will need to be user friendly and ergonomic. Ultimately, the platform's utility will be based on whether it works, "not if there is DLT under the hood," as stated by one workshop participant.

Start in the cloud: Designing in the cloud allows flexibility and saves costs, given updates can be frequent. The cloud allows for updates to occur across all nodes in the system, instead of relying on nodes to independently update.

Design for interoperability: A real challenge in the commercial sector is the intersection of two DLT platforms. Research will be required on how SSACs can build DLT platforms that can be linked to the IAEA and to each other.

Conclusion

Participants saw the value of DLT platforms for safeguards information management and concluded that member states, not the IAEA, would need to drive their adoption at the international level. In particular, participants recognized the technology's potential to drastically reduce the amount of time taken for book inspections, streamline operator and state records, and connect trading partners in the reporting of their bilateral agreements.

While workshop participants initiated a discussion about user requirements, such requirements and the operating conditions into which DLT would be introduced should be tested and validated in one or more prototype ledgers. As researchers conduct field tests of the technology, stakeholders can begin collecting information about the costs of deployment and whether costs would outweigh the benefits. Stakeholders can also discuss which entity would be most appropriate to pay for and drive research on DLT. The small-scale prototype being developed by Stimson and the University of New South Wales for Finland's nuclear regulator will address user requirements for Finland and will assist in framing future testing of blockchain technologies. Another prototype under development by PNNL focuses on using DLT for transit matching at the IAEA, thereby presenting another use case that advances the debate about the utility and desirability of using DLT for safeguards purposes.

Endnotes

1 TradeLens, developed by Maersk and IBM, is a digital platform for businesses and authorities along the supply chain that provides a single security source of shipping data that allows for real-time tracking of shipments. https://www.tradelens.com/solution/.

2 The Stanley Center for Peace and Security and the Stimson Center are nongovernmental organizations. The Pacific Northwest National Laboratory (PNNL) is a federally funded research and development center in the US Department of Energy's Office of Science National Laboratories.

3 Andreas Antonopoulos, "'Blockchain' or Bitcoin: Understanding the Difference," March 16, 2016, https://www.youtube.com/watch?v=mRQs9Y6CUSU.

4 Satoshi Nakomoto, "Bitcoin: A Peer-to-Peer Electronic Cash System," 2008, 1, https://bitcoin.org/bitcoin.pdf.

5 Sarah Frazar, Mark Schanfein, Ken Jarman, Curtis West, Cliff Joslyn, Sam Winters, Sean Kreyling, and Amanda Sayre, *Exploratory Study on Potential Safeguards Applications for Shared Ledger Technology*, Pacific Northwest National Laboratory, February 2017, PNNL-26229.

6 Modum.io is a start-up in Switzerland that combines Internet of Things sensors with blockchain technology, providing data integrity for transactions involving physical products. https://modum.io/system/.

7 Everledger's Diamond Time-Lapse Protocol is a traceability initiative built on a DLT-based platform for the diamond and jewelry industry, https://diamonds.everledger.io/.

8 TradeLens, developed by Maersk and IBM, is a digital platform for businesses and authorities along the supply chain that provides a single security source of shipping data that allows for real-time tracking of shipments. https://www.tradelens.com/solution/.

9 Omar Dib, Kei-Leo Brousmiche, Antoine Durand, Eric Thea, and Elyes Ben Hamida, "Consortium Blockchains: Overview, Applications and Challenges," *International Journal on Advances in Telecommunications* 11, nos. 1 & 2 (2018): 56.

10 Ibid.

11 Sarah Frazar, Cliff Joslyn, Rajveer Singh, and Amanda Sayre, *Evaluating Safeguards Use Cases for Blockchain Applications*, Pacific Northwest National Laboratory, October 2018, PNNL-28050.

[12] Cindy Vestergaard, *Better Than a Floppy: The Potential of Distributed Ledger Technology for Nuclear Safeguards Information Management*, Stanley Center for Peace and Security, October 2018.

[13] International Atomic Energy Agency (IAEA), IAEA Department of Safeguards Long-Term R&D Plan, 2012-2023 (Vienna: IAEA, 2013), accessed May 12, 2016, https://www.iaea.org/safeguards/symposium/2014/images/pdfs/STR_375_--_IAEA_Department_of_Safeguards_Long-Term_R%26D_Plan_2012-2023.

[14] IAEA, *Medium Term Strategy 2018-2023* (Vienna: IAEA, 2018), 13, https://www.iaea.org/sites/default/files/16/11/mts2018_2013.pdf.

[15] IAEA, *The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons*, INFCIRC/153, International Atomic Energy Agency, June 1, 1972, para. 91-94, https://www.iaea.org/publications/documents/infcircs/structure-and-content-agreements-between-agency-and-states-required.

[16] IAEA, "New Web-Based System Streamlines Safeguards Infomation Exchange with IAEA," April 13, 2017, https://www.iaea.org/newscenter/news/new-web-based-system-streamlines-safeguards-information-exchange-with-iaea.

[17] IAEA, MOSAIC: *The Modernization of Safeguards Information Technology*, 2017, https://www.iaea.org/sites/default/files/17/01/mosaic.pdf.

[18] Vestergaard, *Better Than a Floppy*, 3.

[19] IAEA, MOSAIC.

[20] Observation from participant in an exploratory workshop on this subject, hosted in partnership with the Stanley Center for Peace and Security and Cindy Vestergaard of the Stimson Center. The meeting was conducted March 13, 2018, at the Vienna Center for Disarmament and Nonproliferation. All discussions were held under Chatham House Rule.

[21] IAEA, *Report: Symposium on International Safeguards. Building Future Safeguards Capabilities*, July 2019, STR-392, https://www.iaea.org/sites/default/files/19/07/cn-267-symposium-report.pdf; IAEA, *Emerging Technologies Workshop: Trends and Implications for Safeguards*, February 2017, 13–16, https://www.iaea.org/sites/default/files/18/09/emerging-technologies-130217.pdf.

[22] A discrepancy is an inconsistency found in the facility operator's records, or between facility records and state reports, or between these records and inspector observations.

[23] Edward Yu, Edward Obbard, Lan Le, "Evaluation of a Blockchain Based Nuclear Materials Accounting Platform in Australia," IAEA Safeguards Symposium, November 2018, Vienna.

[24] Existing IAEA databases include the operator database, state database, and regional authority database

[25] Vestergaard, *Better Than a Floppy*, 6.

[26] Cindy Vestergaard, *Governing Uranium Globally*, Danish Institute for International Studies, 2015:09, 96–102.

[27] Vestergaard, *Better Than a Floppy*, 6.

[28] Peter Dessaules and Richard Meehan, "Management of Foreign Obligated Nuclear Material in the United States," Department of Energy, National Nuclear Security Administration, and Ali Tabatabai, Link Technologies Inc, paper presented at 60th Annual Institute for Nuclear Materials Management meeting, Palm Desert, CA, July 2019.