Before the Yellowcake: Closing Safeguards Gaps at the Mining and Milling Stages

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Abstract:

The global resurgence of nuclear energy as a sustainable, low-carbon power source is driving a sharp rise in uranium demand, spurred by concerns over energy security, climate change, and the transition from fossil fuels. This surge has prompted both established and emerging nations to expand uranium mining operations, raising urgent challenges for safeguarding nuclear materials. While countries with mature regulatory systems, such as Kazakhstan, must adapt to the scale-up of activities, new entrants face steep implementation hurdles in aligning with International Atomic Energy Agency (IAEA) safeguards. The proliferation risks are particularly acute in politically unstable regions where not established oversight can lead to illicit access to uranium. To address these threats, a collaborative international response is essential, prioritizing regulatory reform, capacity building, and the integration of cost-effective monitoring technologies. This article is a proposal to analyze the key vulnerabilities in uranium supply chains and explores practical, existing, scalable solutions to ensure that the growth of nuclear energy remains secure and peaceful.

Keywords:

Uranium Mining, Safeguards, Proliferation, Illicit Access, Security Threat.

1. The New Global Trends in Uranium Demand and Mining Expansion

In recent years, there has been a global renewal of interest in nuclear energy, largely driven by the urgent increase in power demands, enhanced particularly by the data-center revolution and its surging necessities. This has emphasized the need to transition away from fossil fuels and traditional energy production means, in order to respond to this rising demand and mitigate climate change through low-carbon power generation.[1] Nuclear power is one of the most reliable and scalable sources of low-emission electricity, therefore, governments and private sectors worldwide are reevaluating its role in their long-term energy strategies. This regained interest in nuclear energy has led to a significant increase in demand for uranium, which will likely further grow in the next decade with projections as high as +28%.[2]

To meet this rising demand, uranium mining operations are expanding rapidly across the globe. Established producers such as Canada, Kazakhstan, and Australia are accelerating their production capacities, while new entrants to the uranium market are emerging, often in developing regions with previously unused reserves.[3] This dual course is reshaping the geopolitical and environmental landscape of uranium extraction.

Understanding the implications of this trend requires a close examination of how uranium mining operations are evolving in both scale and geography, and what challenges this evolution entails for global energy security, environmental sustainability, and international regulation. This paper contributes to the discussion by introducing solutions observed from other sectors, before concluding its observations on cross-domain operational experience in securing uranium mining safeguards.

2. From Boom to Breach. Ensuring Uranium in a Shifting Geopolitical Terrain

While established mining countries face the pressure of scaling operations under complex regulatory and geopolitical conditions, newcomer States must confront a steep learning curve in regulatory development, technical expertise, and national and international compliance.

Safeguarding uranium requires not only technical infrastructure but also a secure environment and political stability, transparency, and alignment with the International Atomic Energy Agency (IAEA) and larger non-proliferation standards. This section explores the evolving dynamics in both contexts, emphasizing the need for coherent global standards and capacity-building mechanisms to prevent security, environmental, and proliferation-related risks from escalating alongside uranium production.

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2.1. Safeguards Challenges for Uranium Mining

International safeguards for uranium mining are primarily governed by the IAEA's verification regime, comprising the Comprehensive Safeguards Agreements (CSAs) and the Additional Protocol (AP).[4] The primary aim of the CSAs is to ensure the timely detection of any diversion of nuclear material from peaceful uses to potentially military or undeclared activities.[5] However, their scope, as outlined in the document INFCIRC/153, explicitly excludes the application of safeguards to materials at the mining or ore processing stages.[6]

In practice, this means that safeguards only come into effect once uranium reaches a form suitable for fuel fabrication or enrichment, typically, after it has been processed into yellowcake (U_3O_8). While States are obligated to declare uranium mines and associated activities, the IAEA does not routinely inspect mining facilities, resulting in limited oversight at this early stage of the nuclear fuel cycle (Table 1).

Table 1. Applicability of IAEA safeguards to uranium mining and milling. [4]

Fuel Cycle Stage	CSA	AP	Voluntary Agreement
Mining & Milling	**Declaration only (1)**	**Yes (2)**	No
Conversion	Yes	Yes	No
Enrichment	Yes	Yes	Yes
Fuel Fabrication	Yes	Yes	Yes
Nuclear Reactor Operation	Yes	Yes	Yes
Spent Fuel Storage	Yes	Yes	Yes
Reprocessing	Yes	Yes	Yes
Waste Storage or Disposal	Yes	Yes	Yes

(1) There are no routine inspections; safeguards are not applied until after conversion under the CSA scheme.

(2) Subject to the negotiated AP, there are cases of AP excluding uranium ores/residues and leaving mines outside of coverage.

It should be clarified that while the CSA requires States to declare the existence of uranium mining and milling activities, it does not prescribe to undergo verification or inspections at this stage. CSAs formally begin only once uranium has been processed into a form suitable for enrichment or fuel fabrication. This explains the apparent discrepancy between Table 1 and Figure 1: the CSA establishes a declaration obligation, but not operational safeguards. The Additional Protocol can strengthen this transparency, but its provisions differ from state to state, meaning that early-stage activities remain unevenly covered worldwide.

The Additional Protocol (AP) was developed to strengthen the existing safeguards regime by increasing the transparency of nuclear-related activities. If in the scope of the agreement, under the AP, signatory countries are required to declare all uranium mines and milling facilities, submit annual reports on outputs and transfers, and allow the IAEA short-notice access to the sites.[7] The protocol also permits environmental sampling to help detect undeclared nuclear activities. But the AP is a voluntary measure. As of 2025, it is in force in 144 countries and those under the EURATOM treaty, while 12 others have signed but not yet implemented it.[8]

Together with the IAEA Safeguards system, export control mechanisms further contribute to the international governance of uranium. Countries wishing to trade uranium must meet specific safeguard conditions, most of which are informed by the guidelines established by the Nuclear Suppliers Group (NSG). These include the application of IAEA safeguards to transferred materials, assurances of peaceful use, and commitments to physical protection standards.[9]

The Convention on the Physical Protection of Nuclear Material (CPPNM), along with its 2005 Amendment, establishes legally binding measures for the protection of nuclear materials, including during international transport.[10] While the CPPNM applies specifically to enriched uranium and other classified nuclear materials, many States extend similar protective measures to natural and low-enriched uranium to prevent theft, loss, or sabotage during transit.

Despite these frameworks, the regulatory system faces notable limitations. Among them is the voluntary nature of key agreements, such as the Additional Protocol, and the inconsistent global application of physical protection measures. In the case of uranium transport and trade, while safeguards are widely applied by IAEA Member States, physical protection measures are still largely non-mandatory and vary significantly across jurisdictions.[11]

The lack of uniform global standards and the limited application of safeguards to mined uranium (Figure 2) pose considerable challenges, particularly as the industry scales up to meet increasing global demand. In this context, the effectiveness and comprehensiveness of safeguards frameworks will be crucial in ensuring the secure and responsible development of uranium resources.

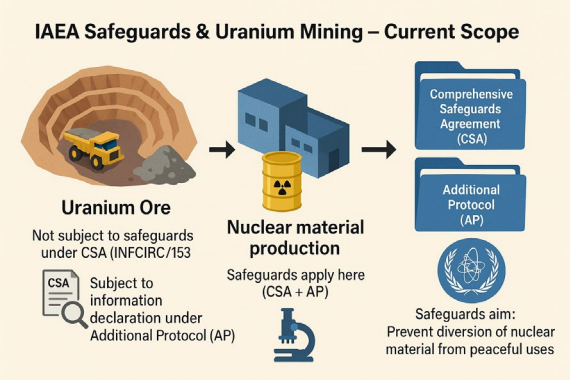

Figure 1. Introductive IAEA Safeguards Verification Mechanism & Uranium Mining.

2.2. An Inside Look at Established Mining States

Established producing countries hold the technical expertise and infrastructure to respond quickly to the surging global demand for uranium. However, scaling efforts are exposing structural weaknesses in existing national frameworks, revealing a common set of challenges across diverse political and economic systems.

Table 2. World Top Uranium Mining Countries.[12]

Country	Global Share	Major Mine/Company	AP	AP Applied
Kazakhstan	~40 – 45%	Kazatomprom	In force 2007	Declares mining and milling activities; site access.
Canada [49]	~15%	Cameco (Cigar Lake, McArthur River)	In force 2000	Declaration of detailed info on facilities; +inspections
Namibia [50]	~10%	Rössing, Husab	In force 2012	AP with declaration duty
Australia [51]	~9%	Olympic Dam, Ranger (closed)	In force 1997	Declaration on mining and milling, not for raw ores
Uzbekistan [52]	~8%	Navoi Mining	In force 1998	AP excluding ores and residues
Russian Federation [53]	~6%	ARMZ	/	Voluntary AP including mining and milling for peaceful uses of nuclear energy (Article II, iv)
Niger [54]	~4%	Orano (suspended), SOMAÏR	In force 2007	Declaration of uranium mining activities.

A central issue lies in adapting existing safeguards and regulatory protocols to match the increased volume and complexity of mining activities. While many top producers are signatories to the IAEA's Additional Protocol, as seen in the table above, not all have implemented it. While Kazakhstan, Canada, and Australia have some of the most robust AP

mechanisms in place, countries like Namibia, Uzbekistan, and Russia remain outside their full scope.[13] This uneven commitment leaves significant portions of global uranium production subject to limited international oversight.

In addition, an increased production can often outpace the capacity of national regulatory systems. In Canada and Australia, for example, scaling efforts are slowed by long permitting processes and growing public scrutiny over environmental protection and sustainability, particularly from autochthonous groups and environmental organizations.[14] On the other end, countries with more centralized control (e.g., Kazakhstan and Uzbekistan) may expand more rapidly at the cost of transparency and environmental accountability.[15]

Environmental concerns, particularly around in-situ recovery (ISR) methods used in Kazakhstan, are intensifying, with worries over groundwater contamination and long-term ecosystem damage.[16] Water scarcity, a critical constraint in Namibia and parts of Australia, also poses physical limits on mine expansion.[17] At the same time, climate-related risks, such as flooding in Canada's northern regions, threaten the sustainability of existing operations.[18]

Another common threat is economic and infrastructural fragility. While several countries are ramping up production through reactivated mines or new exploration licenses, they remain vulnerable to capital shortages, fluctuating prices, and supply chain disruptions. Many operations rely on sensitive logistical corridors (e.g., through Russia or China), which can suffer from discontinuity, while the mining sector struggles to attract and retain skilled labor.[19]

Security risks are also growing and cannot be disregarded in safeguard concerns. From cyberattacks on mining infrastructure to theft or sabotage during transport, the sector must now face a broader threat environment than in previous decades.[20] These vulnerabilities are worsened by geopolitical instability, as seen with Kazakhstan's 2022 political unrest, or the shifting trade landscape due to multilateral sanctions on the Russian Federation.[21]

Despite their differences, established uranium producers share a common need: to modernize safeguards, strengthen regulatory systems, and adapt operational frameworks to a more volatile and scrutinized global context. Without addressing these structural gaps, the promise of uranium as a strategic low-carbon energy source may be undercut..

2.3. Emerging Mining States and Their Challenges

Together with traditional uranium mining States, a growing number of countries are moving to develop domestic uranium mining industries. For these new entrants, uranium represents not only a potential energy source but also a path to economic diversification and geopolitical relevance. However, the transition from exploration to secure and responsible safeguarded production presents its challenges (Figure 3).

A core issue is the limited experience many of these States have with nuclear materials. Uranium mining demands a precise set of safeguards and safety procedures that few newcomer countries have experience with. Tanzania, for instance, has advanced to the near-production stage with projects like Mkuju River. However, its regulatory framework remains limited, and critical infrastructures, such as roads, power, and water, are often behind industrial requirements.[22] The country’s uranium sector has also been influenced by political uncertainty and delayed investor confidence following an earlier government-imposed moratorium. These factors might foster the risk of poor oversight, environmental contamination, or the illicit diversion of materials.

Even countries with advanced scientific or industrial capacity face challenges. India, for example, is working to expand domestic uranium production to meet the needs of its growing nuclear fleet, but faces significant obstacles, including low ore grades, complex geology for working conditions, and strong opposition from environmental and Indigenous groups.[23] India has also to face its historical exclusion from global uranium markets, for not being a signatory of the Nuclear Non-Proliferation Treaty (NPT). This has left the country with limited international partnerships and a heavy reliance on imports, increasing its vulnerability.[24]

Mongolia presents a different but equally interesting case. While rich in uranium potential, its remote geography, harsh climate, and nomadic land-use traditions complicate exploration efforts. Its reliance on Chinese and Russian partners for technical and financial support adds geopolitical complexity, with uranium emerging as a tool of broader strategic competition in the region.[25] Similarly, Argentina’s ambition to integrate uranium into a domestic nuclear fuel cycle is constrained by economic instability, investor hesitation, and decentralized governance between the federal

and provincial authorities delays deployment. Although exploration is progressing, financial crises and overlapping jurisdictions have, for now, hindered momentum.[26]

Other emerging players bring additional risks into the equation. Iran continuously operates to expand its uranium mining capacity by enlarging existing mines and opening other minor ones.[27] All this under the shadow of sanctions, limited IAEA access, and widespread concerns about the military dimensions of its nuclear program.[28] Cyberattacks have already targeted Iran's nuclear infrastructure, underlining the serious risks associated with insufficient transparency and trust. Greenland, on the other hand, represents a case where mining projects were once approved but later reversed due to domestic political shifts. The fragile Arctic ecosystem, together with rising nationalist sentiment, has made the future of uranium mining in the region profoundly uncertain.[29]

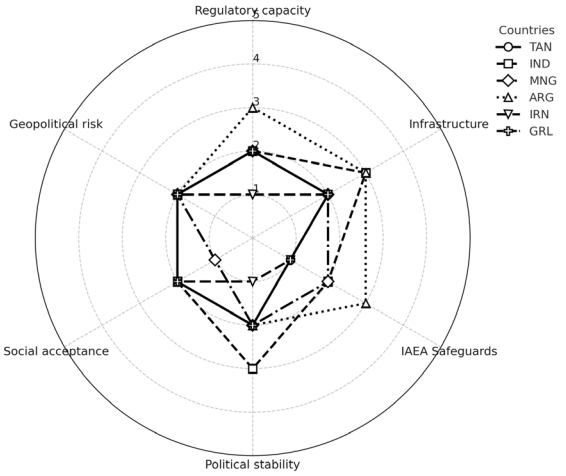

Figure 2.

Across all these cases, several trends emerge. Newcomers often struggle with knowledge transfer, on how to train regulators and technicians to meet international standards from their starting point. They face infrastructure deficits, limited domestic expertise, and political instability that can derail long-term planning. Even where uranium is seen as an economic opportunity, projects are frequently met with domestic resistance over safety and environmental concerns. And without a strong and transparent safeguards regime, these projects can quickly become sources of international preoccupation and mistrust.

Failing to address these vulnerabilities could expose both emerging producers and the broader nuclear industry to serious instabilities and risks.

3. Leveraging Existing Tools and Frameworks to Enhance Uranium Safeguards

As previously introduced, the rising global demand for uranium has been increasingly putting to the test the capacity of existing safeguards frameworks and national regulatory systems. In light of the challenges outlines, from uneven safeguards implementation to growing vulnerabilities of established and emerging uranium producers, this section outlines solutions aimed at reinforcing international norms, closing oversight gaps, and enhancing cooperation among key stakeholders—including governments, the IAEA, and the private sector—to ensure that uranium mining and trade remain secure, accountable, and aligned with peaceful use commitments.

Instead of reinventing the wheel, a more pragmatic approach involves adapting and scaling existing technologies, frameworks, and cooperative mechanisms that have demonstrated success in other sectors or regions. The following strategies offer scalable and cost-effective solutions for enhancing uranium safeguards worldwide.

3.1. Low-Cost Remote Monitoring and Surveillance

Advances in satellite imagery and open-source intelligence (OSINT) have created opportunities for resource-constrained states to monitor uranium mining activities without the need for costly infrastructure. Platforms like Google Earth Engine[30] and Sentinel Hub[31] provide free, high-resolution satellite imagery and geospatial tools capable of identifying new mining sites, tracking operational changes, and detecting anomalies. This method has already proven effective in environmental and resource monitoring, such as tracking deforestation in Brazil[32] and illegal mining in Ghana.[33]

However, reliance on open-source tools carries inherent risks, including potential data misinterpretation, limited legal admissibility, exposure of monitoring activities, and vulnerability to access restrictions or misuse by malicious actors.

In regions observing turmoils, e.g., Niger, where security threats and regulatory gaps persist after the July 2023 military coup, these tools could

assist in monitoring uranium mining operations at sites like Arlit and Imouraren, serving as an early warning system for potential diversion risks.

Complementing satellite monitoring, crowdsourced platforms such as Ushahidi[34] - originally designed to report social unrest - could be repurposed for uranium safeguard purposes. Local communities can anonymously report unauthorized activities or security breaches, providing real-time intelligence that can be verified and acted upon by authorities. The verification costs, however present, will likely be significantly lower than an entirely structured monitoring system.

3.2. Mobile Safeguards and Training Platforms

To address the human capital gap in emerging uranium producers, mobile-based training and compliance tools offer an accessible and scalable solution. The IAEA's e-learning platform[35], already globally accessible, can be adapted into mobile applications tailored for uranium mining personnel. Such platforms could include multilingual content (e.g., in Hindi or Urdu) to improve accessibility in South Asia.

For operational compliance on-site, tools like i-SAFE are already used in South Africa for transports and first response across several fields. It could enable inspectors to conduct safety checks and log data in real time. A similar approach could benefit countries like Uzbekistan, where mining is significant but oversight mechanisms remain under development.

3.3. Simplified Material Control and Accounting Systems (MC&A)

While advanced MC&A systems such as RFID-based tracking may be out of reach for many countries, simplified and cost-effective alternatives can be just as effective and far more available. For example, the United States[36] has implemented barcode systems to track and safeguard material flows within its large-scale operations. Meanwhile, most countries continue to rely on structured manual reporting methods, which, when aligned with IAEA guidelines, especially in terms of information security, can still fulfil safeguard requirements.

The IAEA could further support these efforts by providing standardized, user-friendly templates for inventory tracking and material accounting, allowing new entrants to uranium mining to build foundational safeguard capabilities without major technological investment.

3.4. Strengthening Regional and International Cooperation

Shared regional frameworks can extend safeguards impact through coordination, information sharing, and peer accountability. Special Reportings under the Treaty of Tlatelolco at OPANAL illustrate how collective safeguards infrastructure can be established across neighboring states.[37]

International training initiatives like the IAEA's Technical Cooperation Programme[38], and centers such as the Nuclear Security Training and Support Centre in Malaysia[39], demonstrate how pooled resources can develop safeguard capacities across entire regions. Similarly, the European Commission's Joint Research Centre (JRC) model of peer review[40] and expert exchange could be replicated for uranium mining, enabling countries like Canada to mentor states such as Namibia or Uzbekistan in regulatory best practices.

3.5. Enhancing International Monitoring and Peer Support

The creation of robust, international peer networks is critical for combating illicit trade and ensuring transparency across borders. The INTERPOL Environmental Crime Programme[41], can be leveraged for cross-border cooperation on uranium trafficking, such as a proposed joint uranium monitoring mechanism between newcomers: Zambia and Tanzania.

Open-access databases - modelled after the IAEA's International Nuclear Information System (INIS)[42] - could support transparency in uranium tracking and trade. Meanwhile, simplified, cloud-based versions of the IAEA's e-safeguards system would allow resource-constrained countries to engage in electronic reporting without the need for advanced digital infrastructure.

3.6. Affordable Security Measures for Uranium Transport

Transporting uranium ore is a vulnerable stage in the supply chain, especially in regions with limited law enforcement capacity. Here, basic but effective tools like low-cost GPS trackers, widely used in African logistics chains[43], can help maintain visibility of shipments. Similarly, tamper-evident seals, employed in mining operations across South America[44], provide simple physical barriers to prevent unauthorized access.

3.7. Reducing Dependence on Uranium Through Technological Diversification

Long-term solutions to reduce pressure on uranium supply chains include diversifying the nuclear fuel base. Thorium Fuel Cycle programs exemplify how alternative materials can lessen uranium dependency. Countries may also explore Small Modular Reactors (SMRs) and fast breeder reactors, which use fuel requiring less uranium input. China's investment in new nuclear designs and technologies[45] and France's experience with plutonium breeders[46] showcase the feasibility of such transitions.

Yet, this aspect would constitute a simple transfer of concerns to another material or to another stage of the fuel cycle. The safeguards systems, including the most complete ones existing today, will still need to undergo modernization to adapt to new proliferation, safety and security challenges.

3.8. Strengthening National Legal Frameworks

National legislation remains the cornerstone to operationalizing nuclear safeguards. Argentina sets a strong precedent with its legal alignment to IAEA standards and an independent regulator overseeing all stages of uranium handling according to its agreements with the IAEA and ABACC[47]. Brazil, working through CNEN and in close cooperation with ABACC, demonstrates how localized nuclear security units under national oversight can combine physical protection and safeguards reporting effectively. . These teams are trained at the national level yet embedded in uranium-producing regions, making oversight more responsive and cost-effective while promoting community-level trust and compliance. [48]

Comparable independent or regional frameworks exist elsewhere, for instance, the Canadian Nuclear Safety Commission (CNSC), Australia's ANSO, and the EURATOM inspectorate system in Europe. These cases demonstrate that multiple institutional designs can achieve high levels of uranium oversight.

For emerging producers, these examples demonstrate two important lessons: the value of strong legal obligations from the earliest stages of the fuel cycle and the feasibility of regionally embedded safeguards enforcement.

These models show that legal clarity, local enforcement, and early-stage regulation can significantly enhance uranium governance, especially in emerging producer states.

4. Conclusion: Uranium Security through Operationalizing Safeguards in Practice

Despite uranium's foundational role in the nuclear fuel cycle, its early stages remain the least protected. Safeguards, physical security, and transparency measures often fall short at the very point where diversion and vulnerability begin: the mine. This disconnect between downstream controls and upstream exposure is no longer sustainable. As more states enter the uranium market and established producers scale up, the front end of the cycle has become a critical bottleneck in the global nuclear governance system.

Rather than calling for sweeping reforms, this paper has outlined a set of targeted, scalable solutions. These respond directly to current vulnerabilities, ranging from legal blind spots and insufficient IAEA reach to physical protection shortfalls and regulatory underdevelopment. The table below (Table 3) maps these solutions to the specific challenges they are designed to address.

Table 3. Matching Safeguards Solutions to Uranium Mining Challenges.

Challenges	Solutions
1. Lack of financial and technical resources for surveillance	Use of free satellite imagery tools (e.g., Google Earth Engine, Sentinel Hub); Crowdsourced monitoring via open-source platforms (e.g., Ushahidi)
2. Limited access to training and human capacity development	Mobile apps for IAEA e-learning and compliance training; Regionally adapted training modules in local languages (e.g., India, Pakistan); Joint IAEA regional training centers (e.g., Malaysia)
3. Weak on-site safety and protocol compliance monitoring	Mobile-based monitoring tools (e.g., i-SAFE in South Africa); Localized nuclear security units (e.g., Brazil)
4. Inadequate material tracking and accounting systems (MC&A)	Barcoding systems for uranium tracking (e.g., Kazakhstan); Structured manual reporting templates supported by IAEA (e.g., Niger)

Challenges	Solutions
5 .Lack of regional and international cooperation or data exchange	Regional frameworks (e.g., Pelindaba Treaty, OPANAL) Peer review and expert sharing via EU's JRC; International training programs (e.g., IAEA Technical Cooperation Program)
6. Weak transport security and risk of diversion during shipping	Low-cost GPS tracking in transport (e.g., Logistics Africa); Tamper-evident physical seals (used in South America)
7. Cross-border illegal trade and insufficient border monitoring	INTERPOL Environmental Crime Programme Bilateral regional monitoring agreements (e.g., Zambia-Tanzania model)
8. Limited transparency in the uranium supply chain	Global open-access database modelled after IAEA-INIS ; Cloud-based e-safeguards systems for digital reporting
9. Overdependence on uranium and proliferation risk	Thorium-based fuel cycle (e.g., India) Fast breeder reactors (e.g., France); Small Modular Reactors (e.g., China)

Addressing these uranium mining vulnerabilities will require cross-domain cooperation - linking safeguards, security, safety and sustainability - and drawing on the operational maturity of established uranium producers to guide and support a more accountable global mining landscape.

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