Report of the Limitations Working Group

December 2025

Limitations Working Group and Its Objectives

The Limitations Working Group (LWG) was established to address a fundamental but underexplored question: What kind of verification is required to provide confidence to the international community that a state is staying within a treaty-defined limit on the number of nuclear warheads it is permitted to possess?

In contrast to dismantlement-focused reductions scenarios, which emphasize a state's reduction from its current number of nuclear warheads to a lower number of warheads (and ultimately zero), limitation scenarios aim to establish methods to achieve confidence that a state is not exceeding an agreed upon maximum number of nuclear warheads over the life of an agreement. The LWG was charged with developing tools, procedures, and conceptual models supporting balanced, effective, and practical verification in an active and operational nuclear weapons enterprise (NWE).

To tackle this challenge, the group launched several workstreams including:

- **Lifecycle of a warhead.** Using a systems approach to understand where inspection resources can be best focused and what percentage of the entire stockpile is available for inspection at any given time
- **Diversionary pathway analysis.** Examining where and how a state might attempt to retain or produce undeclared warheads or their components

- **Portal monitoring and related technologies.** Exploring how to control and monitor ingress and egress at key sites
- **Concept of Operations (CONOPs) development.** Focusing on developing inspection protocols that are operationally realistic.

The LWG's work builds on earlier IPNDV phases and conceptual foundations, but it marks a significant pivot toward verification under a discrete and realistic scenario, both in terms of setting a specific limit to what is being verified, and how that limit is interpreted and enforced in practice.

In this paper we discuss potential pathways for diversion of nuclear warheads or warhead components and the potential impact of radiation shielding materials, which complicates the work of the inspectors. We also review a number of tabletop exercises that were carried out by the LWG, and finally we provide a summary of the insights gained by the Working Group, as well as the group's recommendations for further work.

Limitations Scenario

At the outset of Phase III, the IPNDV took a major step forward in its scenario-based approach by articulating a detailed, notional nuclear-armed state—Ipindovia (Figure 1)—and its disarmament obligations under a hypothetical multilateral Nuclear Weapons Limitation Treaty (NWLT). Under the treaty, Ipindovia and other state parties agreed to limit their nuclear arsenals from 1,000 to 500 nuclear warheads.

Figure 1. Ipindovia's Nuclear Weapons Enterprise

IPNDV

This map has been prepared to support the Phase III work of the International Partnership for Nuclear Disarmament Verification. As a basis for analysis of verification of disarmament obligations, it depicts nuclear-weapon sites, infrastructure, and other relevant sites in a notional nuclear-armed country. For more about the IPNDV, visit: www.ipndv.org.

Building on the Partnership's earlier focus on reductions and dismantlement, the LWG then focused on the verification requirements for the post-reduction phase, one in which compliance with the 500-warhead limit would need to be continuously monitored in accordance with the NWLT:

> The NWLT is a multilateral treaty including both nuclear weapon-possessing and non-nuclear weapon-possessing states. As a State Party to the NWLT, Ipindovia is obligated to limit its arsenal to no more than 500 nuclear warheads for 20 years

> following entry into force. Its existing operational NWE and the absence of undeclared warheads are to be verified during the life of the treaty. The NWLT does not prevent Ipindovia from refurbishing existing warheads or producing new warheads, so long as the overall stockpile never exceeds 500.

Under the NWLT, the required verification is carried out by a multilateral entity, the Multi-State Verification Body (MSVB), composed of nationals from both nuclear-weapons and non-nuclear-weapons states party to the treaty. The verification regime includes a range of declarations and notifications to help the MSVB plan, prepare, and conduct verification activities as well as to track implementation of the NWLT:

- **Baseline Declarations.** Following entry into force of the agreement, all parties must make an initial declaration identifying all nuclear weapons on their territory or on territory under their jurisdiction or control, all facilities where nuclear weapons may be located, and other nuclear weapons infrastructure such as delivery systems, fissile material production facilities, nuclear weapons research and development facilities, and storage, maintenance and dismantlement facilities. The parties also are obligated to provide site diagrams of facilities subject to the NWLT.
- **Periodic Declarations.** At least annually, parties to the NWLT are obligated to provide an update of all the data contained in the Baseline Declaration submitted to the MSVB.
- **Notifications.** Parties are obligated to notify the MSVB of movement and changes in the locations of nuclear weapons subject to the NWLT and of changes to the status of facilities declared under the NWLT.

The NWLT provides for the following types of inspections by the MSVB:

- **Baseline Inspections***.* To confirm the initial baseline declaration, including declared facilities, their associated site diagrams, and the treaty accountable items (TAI) declared to be located at or in those facilities.
- **Recurring Short Notice Data Confirmation Inspections.** To confirm the accuracy of declarations at operational facilities as well as confirm notifications of activity under the NWLT (e.g., the movement of a nuclear warhead from one location to another).
- **Challenge-type Inspections.** To *confirm* absence of non-declared TAIs at undeclared and formerly declared sites and facilities (i.e., at sites and facilities that are not or no longer declared to be part of the NWE).

Furthermore, the NWLT provides scope for the agreed addition of inspections by the MSVB to accommodate dismantlement, maintenance, and production of warheads over its duration. The permitted number of inspections per year was limited.

In its work, the LWG explored how a limitations regime could be structured to ensure that a numerical limit was not only declared, but effectively verifiable. The LWG drew on real-world arms control precedents as well as prior findings from across the IPNDV, recognizing that sustaining trust in a treaty-limited arsenal poses unique verification challenges distinct from those in a reductions to zero scenario.

Systems Approach to Verification Under Limitations

A systems approach aims to apply a comprehensive, enterprise-level perspective to verification, linking facility-specific measures to broader trends in nuclear warhead movement, lifecycle, and operational patterns. In a limitations scenario, this implies that the entire NWE must be considered from a systems-level perspective, and any changes or modifications must be evaluated. The verification studies and discussions described in this report were generally designed with such an overall enterprise-level approach in mind.

The Importance of Monitoring and Verification in Limitations Scenarios

To support its analysis, the LWG developed operational concepts, verification regimes, and monitoring and inspection tools tailored to a limitations scenario, coordinating closely with the Reductions, Technology Track, and Concepts Working Groups to ensure coherence across IPNDV efforts. Rather than focusing solely on technical feasibility, this work aimed to stress test the practical implementation of a treaty limit under real-world conditions. This required addressing several foundational questions:

- How to define what counts as a nuclear warhead when different configurations, such as partially assembled weapons and items in refurbishment or long-term storage, might blur the line
- How to maintain continuity of knowledge over time across inspection intervals
- How to build sustained confidence in declared numbers when not all warheads are available for inspection at all times. The concept of "running knowledge," which is defined as a persistent, verifiable understanding of a state's NWE, emerged as a central objective to building confidence in treaty compliance.

Refurbishment added another layer of complexity. Unlike in a reductions to zero scenario, which permanently remove warheads, a limitations scenario involves an ongoing operational NWE, which includes recurring maintenance and refurbishment of warheads to sustain the arsenal. This fact makes it hard to distinguish legitimate maintenance from undeclared remanufacturing, which could add warheads to the arsenal rather than keeping it static. Effective monitoring of refurbishment cycles and warhead movements was therefore seen as essential to ensuring that new weapons were not being clandestinely introduced.

Verification under limitations scenarios places an emphasis on confirming the absence of undeclared warheads, warhead components, and associated activities. This requires a heightened dependence on risk analysis. The LWG adopted a "holding-at-risk" framework that prioritizes monitoring and inspection resources based on assessed risk rather than attempting to verify every item at all times. The group also worked to balance inspector and host perspectives, ensuring that confidence-building and non-intrusiveness remained core verification principles.

Also important to the LWG was the impact of facilities that formerly held nuclear weapons. The LWG scenario explicitly states that from Ipindovia's previous nuclear disarmament commitments several former nuclear weapons facilities would exist at the start of the NWLT. Therefore, former nuclear weapons facilities, particularly in the operational structure of an active nuclear weapons program, were considered a key issue for the LWG to address.

The work of the LWG is a critical contribution to IPNDV's third phase, complementing efforts by the Reductions and Cross-Cutting Concepts Working Groups and drawing on lessons learned from earlier exercises. Looking to the future, the insights and tools developed by the LWG provide a foundation for continued innovation in the verification of future limitations treaties—a challenge that will only grow more important in a world where nuclear reductions may not always be immediate, but where arms control limits can still be meaningful.

Identifying and Assessing Potential Diversion Pathways

A State Party to the NWLT has several pathways for attempting diversion at both declared and undeclared sites. "Declared sites" are all locations that Ipindovia reported in its baseline and subsequent declarations and are subject to the terms of the NWLT. In contrast, "undeclared sites" are all other locations not declared by Ipindovia to be subject to the NWLT. Among undeclared sites, former nuclear weapons facilities merit particular attention due to the potential utility of their infrastructure.

This section first examines the potential range of diversion pathways in the limitations context, linking plausible host behaviors to observable indicators that inspectors can monitor during baseline and follow-on activities. It then considers the technical challenge, common across many of these pathways, of shielding of nuclear components, warheads, and complete weapons, which complicates detection and identification. Finally, it returns to the practical application of the IPNDV verification toolkit, outlining how specific processes, procedures, techniques, and technologies (PPTT) can be configured to detect or deter diversion at both declared and undeclared sites.

Declared Sites

At declared sites, the focus of the LWG has been on realistic methods a host might use to retain excess nuclear warheads or their components or move them between declared locations without notification. The group has examined specific practices such as:

- Disguising undeclared warheads within non-accountable containers
- Employing shielded containers to complicate detection
- Manipulating container identity by reusing or duplicating unique identifiers (UIDs).

The LWG has also considered the possibility that declared activities at a site could mask undeclared activities in adjacent areas, including vaults or other limited-access spaces.

These cases are valuable as they provide a direct line of sight from diversion methods to observable signals that do not align with the host's declared activities such as:

- Discrepancies in UID checks
- Inconsistencies in reporting
- Anomalies at controlled egress points
- Unexplained movements.

In turn, they point to a tailored package of PPTT—baseline site characterization, boundary definition, controlled access routes, verification of UIDs, radiation absence measurements at various points, and a credible challenge-type inspection option—that can be applied coherently to reduce diversion opportunity and increase detection probability.

Monitoring Declared Sites

Declared sites offer the most structured opportunity for verification. LWG exercises demonstrated how layering technologies such as portal monitors, radiation detectors, and UID systems could help maintain continuity of knowledge at these sites without requiring direct access and inspection to sensitive areas.

For example, radiation portal monitors positioned at facility entry/exit points proved effective in tracking warhead movement when paired with appropriate documentation and tamper-indicating tags and seals. Radiation absence measurements provided a complementary method to confirm that items leaving a site did not contain nuclear material. Managed access protocols ensured that inspectors could gather essential verification data while complying with safety and security requirements. Exercises at simulated sites validated the utility of these layered approaches in confirming declared movements and detecting many unauthorized activities.

However, technical and operational limitations persist. Portal monitoring effectiveness is contingent on infrastructure and treaty-defined access permissions and controls. False positives, shielding, and ambiguous detection signatures introduce uncertainty, especially when nuclear warheads are transported in shielded containers. These findings underscored the importance of integrating container tagging, layered inspection triggers, and random verification checks to mitigate diversion risks.

Inspectors also noted challenges in verifying warhead counts during transport between sites if relying only on stored data or intermittent access, as the interval between inspections would need to shorten for timely detection of diversion. Work by IPNDV partners outside of the Partnership demonstrated that options for timely electronic reporting of warhead movements while still protecting operational sensitivities might be possible, but would require more examination to build confidence in the process' value to the overall stockpile verification.

Undeclared and Formerly Declared Sites

For undeclared sites, the work of the LWG focused on how former nuclear weapons facilities might be repurposed for clandestine functions and on the potential establishment of covert refurbishment or re-assembly locations. This approach explicitly recognizes that not all risk resides inside the footprint of declared infrastructure; diversionary activity may exploit legacy sites with existing utilities, storage, or security features, or shift to small, specialized locations intended to handle parts or subcomponents. Here, the emphasis is on identifying indicators that are accessible to inspectors through agreed visits and, where appropriate, to the inspectorate through national or multilateral technical means between inspections. Although such means are referenced only as a monitoring aid, it is a well-established precedent that such capabilities are not to be interfered with by the host. By connecting each undeclared-site scenario to a set of potential signatures—changes in traffic patterns, unexplained construction or renovation at legacy locations, or movements inconsistent with the host's declarations—this analysis provides a practical basis for recommending PPTT and inspection approaches calibrated to undeclared-activity risk.

A "formerly declared site," is one that had initially been declared under an active agreement regime but was subsequently closed and verified as being completely "decommissioned" with no nuclear weapons-related activities and most of its critical nuclear infrastructure rendered useless or disabled. In such a closeout scenario, measures are applied—such as cutting pipes, filling vessels with concrete, or sealing items of interest— to make it too costly and too observable/detectible for that state party to reestablish the capabilities of those facilities.

Taken together, the declared and undeclared threads reinforce the same operational outcome: a clearer mapping from diversion pathways to observable indicators and to specific PPTT that can be deployed during monitoring and inspection activities. This mapping supports a more structured approach to inspection design, resource prioritization, and anomaly response within the limitations scenario.

Monitoring Undeclared and Formerly Declared Sites

Active verification becomes substantially more difficult at undeclared sites. One key insight from LWG exercises is that former nuclear facilities, especially those with dormant infrastructure, present the highest risk for diversion. Although satellite imagery and pattern-of-life analysis can reveal potential irregularities, persistent surveillance and access are often lacking.

In a scenario focused on a site formerly handling nuclear weapons, LWG members assessed plausible diversion routes and evaluated the effectiveness of short notice challenge-type inspections. Although simulated inspections offered a deterrent value, their operational effectiveness was constrained by the lack of baseline data and limited real-time monitoring. Portal monitoring alone proved insufficient in these cases, reinforcing the need for complementary measures such as:

- National and Multilateral Technical Means, including satellite-based imaging;
- Pattern-of-life analysis of personnel or vehicle activities;
- Open-source intelligence.

These tools help identify suspicious activity and support the selection of inspection resources when full coverage is not feasible.

Regarding formerly declared sites, robust closeout inspection procedures become the vital tool to reducing the risk of such sites being clandestinely "recommissioned." This, coupled with an ongoing process of dedicated monitoring and inspection measures serves to make reuse of these facilities too risky for a state to contemplate.

Diversion Pathways

A series of tabletop and mini-exercises explored diversion pathways at declared and undeclared sites, including former nuclear weapons-related sites. Scenarios examined both internal diversion (concealing warheads or components within a facility) and external diversion (removing and transporting them between sites). The LWG observed that, in general:

- **Declared sites** offer opportunities to blend covert activities with legitimate operations, but they also face routine inspections, meaning that sophisticated shielding, tampering with monitoring systems, or manipulation of tags/seals/UIDs would be required to enable diversion;
- **Undeclared sites** eliminate routine oversight but would require building and maintaining a parallel, covert infrastructure with trained staff and security, creating significant cost, secrecy, and logistics burdens;
- **Former nuclear weapons-related sites** allow reuse of any remaining **nuclear weapons** infrastructure under the guise of conventional or civilian operations, but their historical association with nuclear activities attracts heightened scrutiny, especially under advanced national technical means.

Specialized case studies included the challenges of covert activity at submarine bases, former military installations, research facilities, and test sites. Across all facility types, exercises highlighted the value of robust baseline declarations, multi-layered monitoring (including portal monitoring and satellite observation), and flexible short notice and challenge-type inspection provisions.

A Technical Challenge: Shielding

The various types of nuclear warheads and special nuclear material (SNM) components in storage would be shielded in a variety of ways depending on the radiation signatures they emit. Materials have distinct absorption properties for different kinds of nuclear radiation. The most important types of radiation for verification purposes are gamma radiation and neutron radiation. Furthermore, a states' techniques for warhead shielding may offer additional challenges for the inspectors as the country's nuclear industry may have developed methods involving rarely used materials. In all instances, the process of inserting shielding into a nuclear warhead container results in a substantial increase in its mass.

Gamma Radiation

Gamma radiation can emerge from both uranium and plutonium warheads. An example is provided by the 1989 investigation carried out by Steve Fetter and colleagues who measured radiation from a Soviet cruise missile on board the Soviet cruiser *Slava*.[1] From the measurements, they concluded that most of the emerging gamma lines came from uranium-235 or plutonium-239 decay products, and they were able to identify lines of uranium-238, uranium-232 and plutonium-241 daughter elements, which implied that the Soviet Union had made use of uranium from reprocessed reactor fuel. As per the calculations, the most intense lines from these radionuclides could still be detected at a range of 4–5 meters from the launch tube.

When shielding against gamma radiation, materials such as lead, tungsten, and bismuth are used. However, trade-offs must be made between material properties and costs. For routine shielding against gamma radiation, iron and steel are frequently used due to their cost efficiency and strength. However, for the same attenuation as lead, a thicker and heavier iron shield is needed. Furthermore, in the presence of beta radiation, X-ray production from iron or steel is much lower than from lead or bismuth.

Neutron Radiation

Neutrons have a high degree of penetration capability. The most efficient shielding is provided by materials containing elements with low atomic numbers such as, for example, hydrogen, boron, or lithium. The selection of shielding material is contingent exclusively on the neutron energy.

In practice, the chosen neutron shielding material is usually high-density polyethylene (HDPE). Slowing down fast neutrons can be achieved through the use of graphite or graphite-based materials. Elements like boron, lithium, cadmium, and gadolinium have very good neutron absorption properties for low-energy neutrons (thermal neutrons) and are therefore often used as filler materials. It should be noted that neutron capture within a neutron shielding material typically results in the emission of prompt gamma radiation, which may be detected.

We have seen that a state has several options if it wishes to conceal the radiation emitted from a nuclear warhead from inspectors. However, in all instances, the release of particles cannot be entirely obscured from a trained and well-equipped inspector with the necessary instrumentation. If the inspected party is using neutron absorbers, then neutron capture reactions will produce gamma radiation, which may be detected. If a gamma-absorbing shielding is present, gamma-ray transmission measurements have the capacity to reveal the nuclear warhead behind it.

Limitations Arms Control Exercises

Throughout Phase III, the LWG explored the IPNDV verification toolkit both conceptually and in practical applications. Some PPTT, such as UIDs, portal monitors, and absence measurements, were explored in-depth through tabletop exercises and simulations. Others, like chain-of-custody protocols or inspection notification guidelines, remained primarily conceptual due to time and resource constraints. This dual track helped the group identify techniques that may be technically

[1] Documented in Steve Fetter et al., "Gamma-Ray Measurements of a Soviet Cruise-Missile Warhead," *Science* 248 (1990): 828–34.

feasible and also implementation challenges and operational compromises that may emerge when applying the techniques in a real treaty environment.

The exercises emphasized that although the toolkit contains strong building blocks, effective verification in a limitations regime depends on how those PPTT are sequenced, resourced, and paired with broader CONOPs. Practical applications revealed gaps not only in technologies but also in procedures, such as inspection planning, baseline declaration structure, and inspector-host interactions. These gaps warrant further exploration to ensure PPTT function as intended under real-world conditions.

Lifecycle of a Nuclear Warhead

During their many years in service, each nuclear warhead may be deployed or stored at a number of different locations. They are built, refurbished and eventually dismantled at specialized facilities, and they may be kept in storage for varying durations. As a result, a nuclear warhead can be expected to be transported both within various sites, as well as between sites a number of times during its lifecycle. When in storage, the warheads should be available for inspection by the verification body, but many of the remaining warheads will not be accessible. For example, those that are in transit, deployed on submarines at sea or road-mobile launchers operating away from their bases, or undergoing refurbishment are likely beyond the reach of any verification measures.

As an exercise, the group modeled the likely refurbishment and replacement schedule for Ipindovia's warheads over the NWLT's 20-year duration. Under this specific scenario, the analysis indicated that roughly 20 percent of the stockpile would be unavailable for inspection at any given time due to maintenance or refurbishment while an additional 30 percent may be unavailable for operational reasons—leaving only about half of the warheads available for inspection at any given time. Mapping warhead flows revealed that most pass through the primary nuclear weapons assembly/disassembly facility at some stage, making it a critical node for inspection. Further tabletop exercises tested different inspection allocation models, including concentrating all inspections at that facility versus distributing them across declared active and former sites, and examined trade-offs between recurring and challenge-type inspections. It is important to note, however, that these results are notional, based on the specific makeup of Ipindovia's NWE.

Portal Monitoring at the Production Facility

In April 2024, the LWG ran a mini-exercise on designing and implementing radiation portal monitoring at Ipindovia's primary nuclear weapons assembly/disassembly facility. Scenarios considered varying levels of inspector access (from full perimeter control to restricted monitoring zones) and the trade-offs between coverage, intrusiveness, and sustainability. Discussions concluded that using layered detection systems was the preferred approach. This includes combining radiation portal monitors with checks on container weight and adding tamper-indicating tags/seals to the containers. This would not only provide the inspectors with multiple means to verify that no diversion attempts occurred (or to detect them if they did) but also meet Ipindovia's need to protect sensitive information. Lessons learned reinforced the need for future treaty negotiators to balance verification resource demands with operational feasibility, and to define treaty provisions for decommissioning sites, pre-decommission monitoring, and short notice inspections.

Transport Verification

Drawing on the START treaty's provisions for missile portal monitoring, the group adapted the concept to warhead transport, testing procedures for both inter-site diversion (e.g., from a road-mobile base to central storage) and intra-site diversion (from a storage location within the assembly/disassembly site). Exercises modeled notification requirements, inspection rights, and destination confirmation mechanisms, integrating UID verification, tamper-indicating tags and seals, and container-specific radiation absence/presence measurements. This work confirmed the centrality of chain-of-custody procedures during transport and identified practical constraints such as inspection timing, ability to use equipment in the field, and host sensitivity to revealing routing information.

Diversion Detection Feasibility

A mini-exercise examined whether 25 warheads could be removed from a central storage site without detection. Results indicated that such diversion would be extremely difficult under the proposed portal monitoring-based verification regime, validating earlier modeling and reinforcing the role of portal monitors in deterrence and detection.

Verification-by-Design

In previous IPNDV work, the pros and cons of using existing facilities for nuclear warhead dismantlement versus building dedicated facilities for verification activities were explored. The cost and time required to build a new dedicated dismantlement facility were significant factors. However, it was also noted that the cost associated with retrofitting an existing facility could be equally high, especially if all the preferred features are met balancing the inspectors' need for confidence that dismantlement was completed and no diversion took place with the host's need to protect proliferative and otherwise sensitive information and maintain safety. To this end, a dedicated Verification-by-Design exercise explored how dismantlement facilities could be designed to incorporate verification requirements from the outset, whether building new or retrofitting existing ones. Across multiple design proposals, common features included unidirectional material flow to simplify monitoring, restricted and size-limited entry and exit points to reduce opportunities for diversion, integrated portal monitors and CCTV at key chokepoints, as well as separation of nuclear and non-nuclear material handling areas. The design proposals also incorporated secure inspector workspaces, equipment storage areas to maintain chain of custody over monitoring and inspection equipment, and perimeter intrusion detection systems. Some designs added features such as directional radiation monitoring to confirm movement direction, break beams, and gamma-ray detectors. Collectively, these concepts demonstrated that embedding verification measures during design could significantly improve inspector efficiency, reduce the risk of diversion, and reduce the operational burden of compliance for the host. Recognizing the significant challenges of developing purpose-built facilities, the group recognized that the principles identified by the exercise could inform the retrofitting of existing facilities to better address the needs of verification activities.

Concepts of Operation

Since the beginning of Phase III, IPNDV working groups have found the creation of CONOPs addressing the various steps of the 14-step model to be an effective tool for distilling the essential steps of any verification strategy and for demonstrating the logical order of proposed inspection activities. With the development of a CONOPs template, the LWG also used CONOPs to encourage IPNDV partners to think through the links between the desired verification outcomes and the necessary technology and equipment needed to achieve those outcomes. Furthermore, CONOPs are valuable in ensuring consistency in how verification is conducted and ensuring inspectors carry out all the recommended steps.

Using the template, the LWG drafted several CONOPs, including all possible responses at first and then critically analyzing each suggestion in the context of an operational NWE characterized by a limitations treaty.

Key observations from this work include:

- At operational military bases, simplistic verification measures (such as visual inspection and documentation review with minimal measurements) would be more operationally feasible, easier for inspectors to understand and implement, and in turn lead to a more cooperative host/inspector inspection environment;
- Minimizing the impact on operational activities are more supportive to successful verification;
- Verification techniques under limitations and reductions scenarios are increasingly similar the further along the dismantlement process you are as operational sensitivities then lessen their impact.

Lessons Learned and Areas for Improvement

Collectively, the above exercises confirmed that effective verification in an active nuclear weapons environment requires:

- Focusing on critical nodes in the warhead lifecycle for inspection;
- Maintaining multi-layered monitoring and short notice inspection capacity across declared facilities, and challenge-type inspections for undeclared sites, keeping in mind that former nuclear facilities pose a potentially higher diversion risk;
- Embedding features that support verification into dedicated areas for conducting inspection activities within existing facilities to reduce inspector burden and host disruption;
- Maintaining strict chain of custody during transport and between inspection sites;

- Using realistic facility access models to calibrate resource requirements and technological needs.

These findings now provide a foundation for possible future work on refining CONOPs, integrating detection technologies with operational procedures, and developing more comprehensive approaches to deter and detect diversion under a limitations treaty.

The LWG has identified several priorities for strengthening the verification toolkit. Expanding the scope and realism of practical exercises emerged as a key priority. Although tabletop exercises provided valuable insights, more operationally focused activities, such as those demonstrated by NuDiVe and the Quad Nuclear Verification Partnership,[2] would allow for testing of verification concepts in environments that more closely resemble real-world conditions. Future exercises could address transportation security and related verification processes and integrate emerging open-source tools that have become widely available in recent years. Scenario development should also incorporate diverse state and regional security contexts and varying inspection requirements.

Technological development presents both opportunities and challenges. Advances in monitoring systems, data analysis, and detection capabilities offer potential enhancements, yet the absence of clear enforcement or accountability mechanisms for non-compliance remains a fundamental gap. The LWG examined the implications of different treaty structures, such as limitations on deployed versus non-deployed delivery vehicles, and the inspection methodologies they require. Consideration was also given to inspection challenges at former nuclear weapons sites, which may undergo significant, unexpected changes, as well as to environmental and logistical constraints that can impede access.

Warhead transportation continues to be a particularly sensitive activity in the nuclear warhead lifecycle. Unique identifier systems can provide a means of confirming container identity before and after transit without compromising sensitive design information, thereby maintaining the chain of custody between declared sites. However, tamper-resistance over extended transport durations, field-deployable authentication procedures, and mechanical reliability of tamper-indicating tags/seals remain unresolved issues. Portal monitoring equipment could also be optimized through reduced size for easier deployment, automated data logging, improved radiation discrimination, and the use of smart thresholding algorithms to reduce false positives in high-traffic areas while improving material specificity for plutonium or highly enriched uranium.

Radiation absence measurement techniques, particularly when paired with short notice inspections, offer a valuable means of confirming the absence of nuclear warheads or SNM components at formerly declared sites or areas in existing declared sites declared not to contain such items. Nevertheless, current approaches can be time-consuming and vulnerable to background interference. Improved sampling strategies and prioritization methods could focus resources on the most significant inspection targets.

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[2] NuDiVe, https://www.ipndv.org/reports-analysis/nudive-exercise-full-documentation, and the Quad Nuclear Verification Partnership, https://quad-nvp.info.

Finally, the LWG determined that verification approaches should evolve toward a systems-level perspective, integrating multiple measures across the warhead lifecycle, identifying trends in movement, and coordinating inspection activities across sites to reduce reliance on any single measure or location. Such an approach would enhance anomaly detection and strengthen the overall credibility of verification regimes.

Limitations Versus Reductions

Discussions within the LWG underscored how verification in the context of limitations differs from a reductions-focused context and what these differences imply for inspection planning. Under a limitations scenario, most or all aspects of the NWE remain operational, and the analytical focus may not extend much beyond dismantling nuclear warheads. This has practical implications for what inspectors will look for and how monitoring and inspection activities will be organized.

- First, an operational NWE changes the verification landscape. Although possible under a reductions scenario, it is more likely under a limitations scenario that new weapons could be developed, and modernization pressures may emerge as weapons systems reach the end of their operational life. In such an environment, development activity is more visible. Although development alone cannot confirm non-compliance, the associated infrastructure and activity patterns can be harder to deny. This places a premium on observing movements, facility use, and support functions and comparing them to the host's baseline declaration.
- Second, the treaty baseline period is a fixed reference, established at entry into force of an agreement. Over time, inspector confidence can increase as repeated inspections continue to confirm results that are consistent with a state's declarations. Because inspections will take place repeatedly at the same sites, institutional knowledge must be preserved so that successive teams can interpret their observations consistently against earlier experiences. The goal is to protect the continuity of knowledge despite many changes in personnel over the years.
- Third, views differ on whether limitations are "harder" or "easier" to verify than reductions. Some note that reductions would be the simpler because activities are narrower and oriented toward removal. Others argue that limitations would be the easier in some respects because they deal with known quantities and can leverage long-standing relationships. The working takeaway is that limitations present a different mix of challenges: a more dynamic operational picture, and the need to interpret development and modernization signals carefully.

These insights translate into practical considerations. Inspection plans should assume that active operations can affect both outcomes and logistics, and PPTT should be calibrated accordingly. Documentation must be structured so that future teams can consistently compare their observations to earlier data. Anomaly response should be tiered and predictable, recognizing that some deviations are benign whereas others may indicate undeclared activities.

Key Conclusions and Recommendations

Summary of Insights from the Limitations Working Group

During Phase III, the LWG refined verification options for a treaty scenario in which Ipindovia maintains no more than 500 nuclear warheads over a 20-year period. The insights and tools developed by the LWG provide inspiration for future verification of nuclear warhead limitations, a topic that can only grow more important in a world where nuclear reductions may not always be immediate, but where limits may still be meaningful. The group examined verification at key facility types alongside measures to confirm the absence of nuclear warheads at specific locations and detect potential diversion of nuclear warheads and their components.

Practical exercises demonstrated the potential value of portal monitoring for confirming the presence of absence of nuclear warheads/SNM components, verifying the absence of undeclared warheads or components, and maintaining continuity of knowledge during inspection activities. The group also conducted a Verification-by-Design exercise, which identified key verification features that could be embedded into dedicated areas in existing facilities to enhance the conduct of verification activities. This work highlighted design opportunities, such as unidirectional material flow, secure inspector workspaces, and integrated monitoring systems, and discussed some challenges, including the cost, safety, and structural complexity of retrofitting older facilities.

Looking ahead, the Working Group identified several thematic areas for continued work:

- **Rigorous Systems Approach.** Apply a comprehensive, enterprise-level perspective to verification, linking facility-specific measures to broader trends in warhead movement, lifecycle, and operational patterns;
- **Alternative Disarmament Cycles.** Explore different sequencing of operational concepts and their integration with a systems-based verification approach;
- **Verification at Low Numerical Limits.** Assess the unique challenges when treaty limits fall to very small numbers of warheads (for example, in the low tens), including compressed timelines to zero, shifts in deterrence dynamics, and prioritization of dismantlement sequencing;
- **Interaction with Emerging Technologies.** Evaluate how new technologies, such as AI, machine learning, blockchain-based data validation, and remote detection, could affect verification processes, inspector workflows, diversion risks, and political acceptability of measures such as warhead passports;
- **Integration with National/Multilateral Technical Means.** Analyze how NTM capabilities can complement on-site verification in a limitations context, including detection of anomalies and support for short notice inspections;

- **Treaties of Unlimited Duration.** Consider how the absence of a defined treaty end-date could shape verification strategy, cooperation levels, and fallback mechanisms in the event of treaty breakdown;
- **Inspector Support in Multilateral Environments.** Identify the technical, procedural, and logistical support that inspectors require, including secure communications, data integrity protection, and practical solutions to cyber risks;
- **Irreversibility and Delivery Vehicles.** Expand analysis of how irreversibility concepts apply not only to warheads but also to delivery systems, including the implications for treaty implementation.

Future Work

In addition to the thematic areas identified in the previous section, planned future activities should include:

- Broadening the analytical scope beyond the current 14-step dismantlement model to capture a wider range of verification challenges;
- Developing and refining CONOPs for priority scenarios, including mobile intercontinental ballistic missiles, former military sites, and commonly visited nodes in the warhead lifecycle;
- Exploring fallback verification mechanisms to sustain cooperation and monitoring in the event of treaty suspension or termination.

These efforts will build on the foundation established in Phase III, ensuring that verification approaches remain adaptable, technically robust, and viable in the face of evolving treaty obligations and technological change.

About IPNDV the International Partnership for Nuclear Disarmament Verification

The International Partnership for Nuclear Disarmament Verification (IPNDV) convenes countries with and without nuclear weapons to identify challenges associated with nuclear disarmament verification and develop potential procedures and technologies to address those challenges. The IPNDV was founded in 2014 by the U.S. Department of State and the Nuclear Threat Initiative. Learn more at www.ipndv.org.