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Phase III Summary Report: Addressing Complexities and Building Confidence

IPNDV

INTERNATIONAL PARTNERSHIP FOR
Nuclear Disarmament Verification

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The U.S. Department of State and the Nuclear Threat Initiative (NTI) established the International Partnership for Nuclear Disarmament Verification (IPNDV) in 2014 to address the challenges of nuclear disarmament verification. This effort has brought together 30 countries with and without nuclear weapons plus the European Union to identify solutions to those challenges. During the past decade, the Partnership has carried out work in three phases:

- **Phase I: Creating a Conceptual Roadmap**
- **Phase II: Moving from Paper to Practice**
- **Phase III: Addressing Complexities and Building Confidence**

Across these phases, analysis carried out in the IPNDV's working groups has deepened our understanding of the challenges of nuclear disarmament verification and refined proposed monitoring and inspection solutions to those challenges. This report summarizes the work of Phase III, which concluded in December 2025.

Section I. Overview of Phase III

Phase III of the Partnership began in January 2020. This phase built on and extended the scenario-based approach and other legacy analytic tools of earlier phases. As in prior phases, it utilized a changing set of working groups to organize its effort, complemented by exercises and technology measurement campaigns (Table 1).

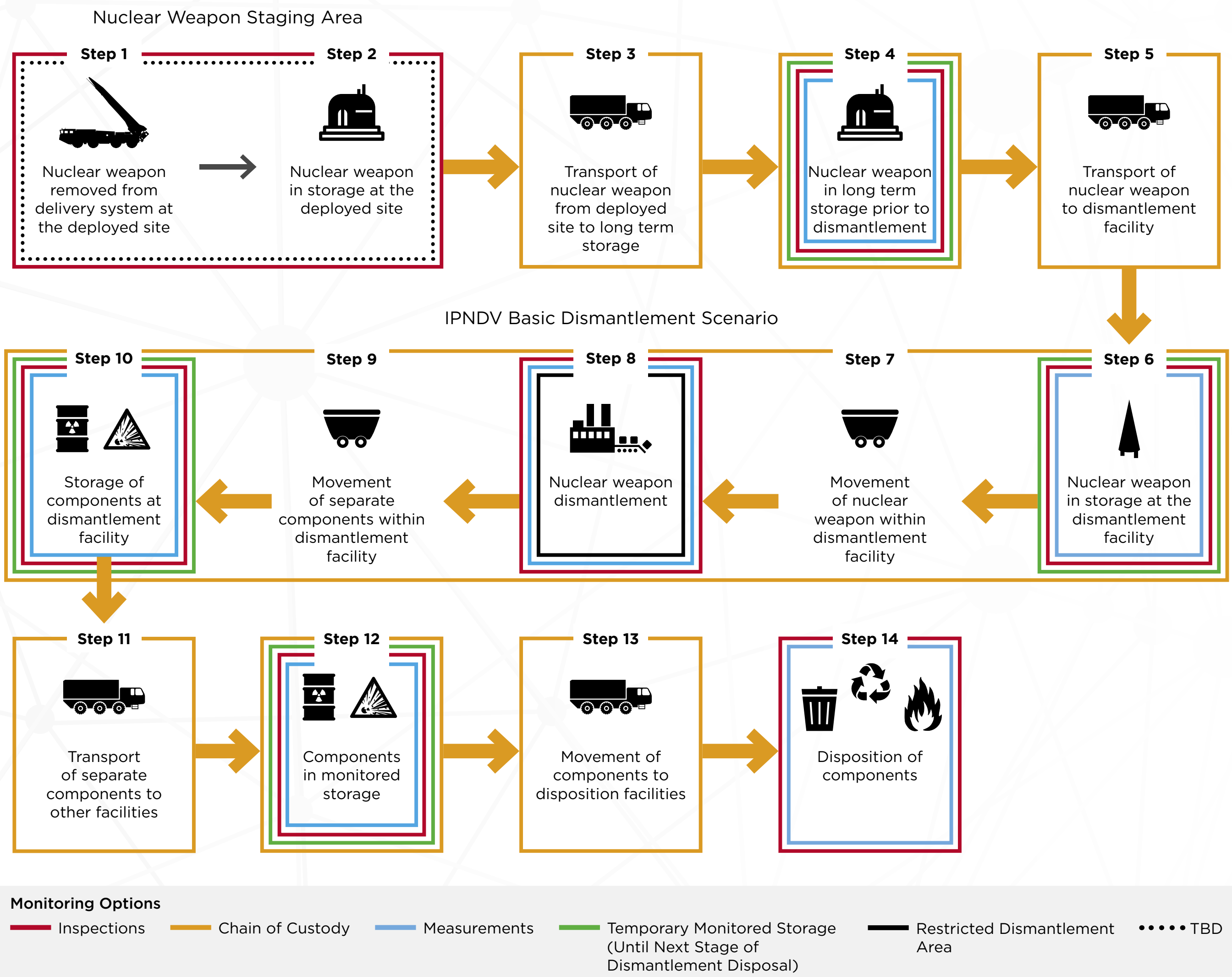
Table 1: Phase III IPNDV Working Groups, Exercises, and Technology Demonstrations

Period	Working Groups	Exercises and Technology Demonstrations
2020–2022	Inspector Task Group (Co-chairs: Australia, Canada, Germany) Host Task Group (Co-chairs: Canada, the Netherlands, United Kingdom) Technology Track (Co-chairs: Germany, Sweden, United States)	Inspection Planning Tabletop Exercise (Virtual, December 2020) Westend ICBM Base Inspection Tabletop Exercise (Virtual, June 2021) NuDiVe 2 (Germany, April 2022—jointly with France) JUNEX 22 Transport-Long-Term Storage Inspection Tabletop Exercise (Belgium, June 2022) Trusted Radiation Identification System (TRIS) and CORIS360 Demonstrations (Australia, December 2022)
2023–2025	Limitations Working Group (Co-chairs: Australia, United Kingdom, Norway) Reductions Working Group (Co-chairs: Germany, the Netherlands) Cross-Cutting Concepts Working Group (Co-chairs: Canada, Germany) Technology Track (Co-chairs: Sweden and United States)	Belgium Technology Experiment—BeCamp 2 (September 2023) Diversion Mini-Exercises (Romania, June 2024, Geneva December 2024, Oslo June 2025) Portal Monitoring Exercise (Geneva, December 2024)

Adapting the Scenario-Based Approach

Phases I and II of the Partnership had developed a basic scenario that focused on verification of nuclear warhead dismantlement as the most demanding part of nuclear disarmament verification.[1] That scenario revolved around a 14-step illustrative model of the nuclear warhead dismantlement process, from removal of a nuclear warhead from its delivery system (step 1) through dismantlement of that nuclear warhead (step 8) to disposition of the special nuclear material (SNM) and high explosive (HE) components derived from the dismantled nuclear warhead (step 14). This model was not intended to be a definitive description but only as starting point. Over time, it has proved a very helpful framework for an evolving analysis of what specific monitoring and inspection options could be applied for verification of the specific steps.

Figure 1: 14-Step Nuclear Disarmament Verification Model



Note: We make the assumption that there will be declarations at each step in the process.

[1] For a detailed description of the IPNDV scenarios and the 14-step model, see "IPNDV Scenarios," February 9, 2024.

When Phase III began in 2020, IPNDV elaborated its scenario-based approach by setting out a more detailed disarmament scenario in which several nuclear-armed countries were parties to a Nuclear Weapon Reductions Treaty (NWRT) under which they were obligated to reduce their nuclear arsenals from 1,000 to 500 deployed nuclear warheads (again within the framework of the 14-step model). As part of this scenario, IPNDV also described in greater detail the nuclear arsenal of one of those parties, a notional nuclear weapons state called Ipindovia, and the detailed verification provisions of the NWRT. While continuing a technology-focused group (the Technology Track), the Partners organized two new working groups, an Inspector Task Group and a Host Task Group. Establishment of these working groups was intended to better illuminate the unique perspectives that inspectors and hosts would bring to the design and implementation of any nuclear disarmament verification regime.

At the mid-point of Phase III in January 2023, the Partners again modified their scenario-based approach by developing two additional sub-variants of the initial Ipindovia reductions scenario. In one scenario, Ipindovia and other parties to the NWRT were obligated to reduce their nuclear arsenals from 500 to zero (reductions to zero scenario); in the second variant, Ipindovia and other parties were obligated to limit their nuclear arsenals to no more than 500 nuclear warheads (limitations scenario). The Inspector and Host Task Groups were replaced by three new working groups. Two of these groups directly tracked the new scenarios: a Limitations Working Group (LWG) and a Reductions Working Group (RWG). The third new working group, the Concepts Working Group, addressed cross-cutting conceptual issues. The Technology Track continued to analyze technologies to support nuclear disarmament verification and provide technical input to the other working groups. Co-chairs drawn from the Partners again guided the separate working group process.

Initially, in 2020 and 2021, because of the COVID pandemic, the working groups and the Partnership conducted all of their work virtually. Their successful engagement is a testament to the Partners' commitment to IPNDV. In-person meetings resumed in June 2022. As part of this process, the Partners also carried out a series of virtual and then in-person exercises during Phase III to test and refine their analytic work. In parallel, smaller ad hoc groups of Partners also organized other exercises as well as technology demonstrations and campaigns.

Insights from Phase III

The detailed insights from Phase III have been set out in a series of papers and reports prepared by the different working groups.[2] These products focus on host and inspector perspectives of verification objectives and declarations; the verification of limitations and reductions of numbers of nuclear warheads (including the detection of diversion of nuclear warheads/components or the undeclared retention or production of nuclear warheads/components in violation of a nuclear disarmament agreement); cross-cutting conceptual issues (including building verification confidence, the

[2] Access these deliverables at https://www.ipndv.org/reports-analysis/.

irreversibility of nuclear disarmament, verification strategies, and options for verification of the disposition of SNM from dismantled nuclear warheads); and the assessment and use of verification technologies. This report summarizes the work done by the Partners in developing those key insights.

Specifically, Section II explores some differences and similarities between how inspectors and hosts are likely to approach future nuclear disarmament verification. Section III summarizes an innovative approach for making choices among specific monitoring and inspection processes, procedures, techniques, and technologies (PPTT) that can be used to verify nuclear disarmament. Section IV focuses on insights for verification of limitations, with particular attention to issues likely to arise in carrying out verification activities amid an ongoing nuclear weapons program. Section V sets out some propositions regarding verification of reductions to zero nuclear warheads, with particular reference to countering possible diversion by bad actors. Section VI highlights selected conceptual insights from Phase III, including related to building verification confidence, allocating inspection resources, and verification of disposition of SNM from dismantled nuclear warheads. A number of considerations related to the purposes, constraints, and use of verification technologies are summarized in Section VII. By way of conclusion, Section VIII then explores possible priorities for further work on nuclear disarmament verification in light of the progress made and gaps identified in Phase III of IPNDV. The report also contains a series of "Perspectives from the Co-chairs or Former Co-chairs" reflecting the personal perspectives on nuclear disarmament verification from the co-chairs of different Phase III working groups.

PERSPECTIVES FROM A CO-CHAIR OF THE HOST TASK GROUP

Nuclear disarmament verification will remain an important area for further development, given that at present such work focuses on the means of delivery: the missiles, the planes, the submarines. As the numerical relation between these means of delivery and the number of nuclear warheads can vary greatly, a more precise determination of the number of nuclear warheads a state possesses becomes even more important when the number of delivery systems becomes small. Counting rules (approximate values for the number of nuclear warheads per missile, plane, or sub) will then not suffice if and when the states with the largest arsenals again talk to each other and the arms control process resumes.

In Phase I, the IPNDV developed a conceptual framework—with its 14-Step Model of the dismantlement process—of what a nuclear warhead verification regime could look like. At that point, the IPNDV could have been brought to a conclusion. Instead, it was agreed to zoom in on specific situations, for example by creating a fictitious state (Ipindovia) with nuclear missile, submarine and bomber bases, nuclear depots, etc. As a result, the Partners learned a bit more about what can realistically be done in a given time span, which instruments one needs at a given location, how host and inspectors negotiate what is allowed and what is not. That was the core of Phase II: scenario-based work. In its early years when I was participating, Phase III continued this work,

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Perspectives from a Co-Chair of The Host Task Group (continued)

hampered by the COVID pandemic, which prevented in-person meetings. With a Host Task Group and an Inspector Task Group, a number of virtual exercises were held and some progress was made at the margins.

Looking ahead, emphasis should be placed on technology development as the most promising way to make progress on nuclear disarmament verification. The IPNDV's work has made clear which types of equipment are necessary for nuclear verification work. Any such verification equipment needs to be developed so that it is optimally suited for work in the field, under operational conditions. The sensitivity of work on verification technologies, the pre-eminence of the United States (and its labs), the (continuous) nature of the work, and expertise of most IPNDV participants, all would shape how to proceed.

More specifically, potential applications of artificial intelligence (AI) to nuclear disarmament verification are an especially important technology development area. AI has propelled International Atomic Energy Agency (IAEA) safeguards forward since the IAEA started developing and using the software a decade ago. Nuclear disarmament verification could profit from a parallel effort.

Conceptually, most of the work has now been done. Plus, while the IPNDV conceptual framework will provide some guidance for future negotiators, they will determine the verification specifics for themselves. However, a few conceptual areas that still warrant exploration include verification over the lifetime of a treaty, approaches to measurements for the presence of SNM (both plutonium and highly enriched uranium), verification of disposition approaches that involve the direct disposal of SNM, and diving deeper into how to ensure chain of custody/continuity of knowledge over nuclear warheads subject to a nuclear disarmament agreement.

Section II. Exploring Inspector and Host Perspectives on Nuclear Disarmament Verification

A central focus of Phase III in 2020–2022 was an assessment of inspector and host perspectives on nuclear disarmament verification, with particular attention to the objectives of each. Carried out by the Inspector and Host Task Groups, this work offers insights into shared and differing inspector and host perspectives related to the negotiation and implementation of a nuclear disarmament verification regime, including the declarations and notifications of treaty-related holdings and activities provided for in an agreement.[3]

Shared and Differing Perspectives on Three Levels of Verification Objectives

Three levels of verification objectives were identified by the working groups (Table 2). These objectives provide an increasing level of detail to facilitate the implementation of a nuclear disarmament agreement.

The treaty's *central verification objectives,* the first level, are set out in the obligations of the agreement, e.g., in a reductions scenario, to reduce the number of deployed nuclear warheads from 1,000 to 500. This objective sets the high-level goal the agreement is seeking to achieve.

Table 2: Levels of Verification Objectives
Level 1: Treaty Central Verification Objectives—legally binding obligations set by the agreement
Level 2: High-level Verification Objectives—confirm/demonstrate compliance, both within unique host requirements for safety, security, and protection of sensitive information
Level 3: Implementation-Specific Objectives—carry out specific activities by inspectors and hosts during the verification process to achieve high-level verification objectives

[3] Host Task Group, "Some Thoughts on Verification Objectives, Declarations, and Their Implications from the Perspective of an Inspecting Entity", December 2022; "Some Thoughts on Verification Objectives, Declarations, and Their Implications from the Perspective of an Inspected State", November 2022.

The *high-level verification objectives* are derived from the central verification objectives and begin to define "how" to achieve them. The Inspector and Host Task Groups concluded that both inspectors and hosts have a shared interest in a verification regime that balances the needs of both sides. Specifically, a regime that provides both monitoring and inspection provisions to allow the inspectors to confirm the host's compliance with those central objectives and allows the host country to demonstrate its compliance with the agreement. In addition, the host will have a high-level verification objective to ensure that any inspection activities do not compromise safety, the security of nuclear warheads and sites, and do not put at risk proliferation-sensitive and other sensitive information. Indeed, for the host, ensuring the safety of nuclear weapons will be an overriding objective that it will not compromise. The host will also have a high-level objective to limit the disruptions of monitoring and inspection activities on ongoing operations.

Again, *implementation-specific objectives* derive from both higher-level objectives, and further define the specific PPTT that inspectors and hosts may utilize to verify compliance with the agreement. Both inspectors and hosts have a shared interest in an efficient, cost-effective regime. This includes well-defined inspection procedures that are practical to implement, the use of accurate and reliable verification technologies, and established procedures for data management. However, important differences persist in the implementation-specific objectives of inspectors and hosts that will be reflected during the negotiation and then implementation of the verification regime.

In principle, the inspectors' perspective, for example, would call for negotiating the most comprehensive possible declarations of treaty-related activities, facilities, and sites at which items subject to the agreement could be deployed. Doing so would provide the most complete starting point for verification, including confirming the absence of any undeclared nuclear warheads. Inspectors also would emphasize more timely notification of changes in declared activities to ensure that their understanding of treaty-related activities is up-to-date. This perspective would argue in turn for more extensive and intrusive monitoring and inspection rights, access, and use of technical equipment. However, this perspective would be tempered during negotiations by the fact that some parties to an agreement would also be hosts because of their possession of nuclear weapons and, thus, subject to those very declarations and inspection provisions.

In principle, providing comprehensive information about treaty-related activities and access to sites engaged in such activities would be consistent with the host's interest in demonstrating compliance. In practice, the host is likely to seek to limit the scope and content of declarations as well as of monitoring and inspection activities in order to protect sensitive information, ensure safety and security, and minimize operational disruptions. Ensuring the security of nuclear warheads would likely lead the host to oppose providing advance notification of the movement of nuclear warheads between sites. How the host strikes the balance between demonstrating compliance and protecting sensitive information while ensuring safety and security will greatly shape the design of the verification regime.

PERSPECTIVES FROM A CO-CHAIR OF THE INSPECTOR TASK GROUP

In Phase II, IPNDV developed key elements for a toolkit of monitoring and inspection options for future nuclear disarmament. Created at the start of Phase III, the Inspector Task Group's (ITG) work strengthened and added further detail to the Phase II toolkit in several respects. The ITG considered selected disarmament scenarios and elaborated possible declaration types and content to facilitate monitoring and inspection activities, as well as concepts of operations (CONOPS) for how an inspection entity may plan and conduct on-site activities at various stages of the 14-step model. ITG members applied many of these results in exercises, gathering feedback to refine them further. The ITG also considered the importance of a systems approach for effective and efficient verification.

Key insights included:

- Scenario-based work is very helpful for investigating the specifics of monitoring and inspecting options in a multi-warhead, multi-site, multi-year disarmament scenario.
- Host country declarations will provide a basis for monitoring and inspection activities but could also include data that may not necessarily be tested routinely. Such data may be included to offer transparency to other parties to a treaty and provide additional assurance by holding certain items/facilities/activities open to ad hoc verification. Various kinds of declarations would be needed: baseline, periodic, ad hoc, and operational.
- Practical testing and exercises should follow a systematic methodology of "test-evaluate-refine-test" so that lessons build on themselves over time. The exercises demonstrated the need to bring further detail to concepts for carrying out various types of inspections.
- The complexity and intensity of on-site inspections can be significant. There is a particular need to consider how to optimize efficiency, both in terms of individual inspections and how results from multiple inspections must knit together to build confidence that monitored items and activities are as declared. This should be at the heart of a systems approach to verification.
- Tabletop exercises are a useful tool, but in-person exercises will likely present more complex issues and challenges and contribute to greater realism.

Over time, the IPNDV has moved to balance more conceptual work, with exercises and other more practical work. Future work must continue to combine conceptual discussions with practical mechanisms to test and refine Partnership findings.

Managed Access Provisions

Given the host's interest in ensuring safety and security in addition to protecting proliferation-sensitive and other sensitive information and limiting operational disruptions, nuclear disarmament agreements typically include "managed access" procedures for monitoring and inspection activities. Table 3 provides some examples considered by the Partnership during Phase III and tested through exercises.

Managed access provisions would set boundaries on inspectors' access to particular sites and define how monitoring and inspection activities would be carried out. Managed access, however, should not prevent inspectors from carrying out necessary verification activities to confirm compliance by the inspected party. In particular, the Inspector Task Group reiterated that hosts have an obligation to find an alternative means of demonstrating compliance in the event that managed access made it impossible to carry out a specific verification activity.

A Dispute Resolution Mechanism

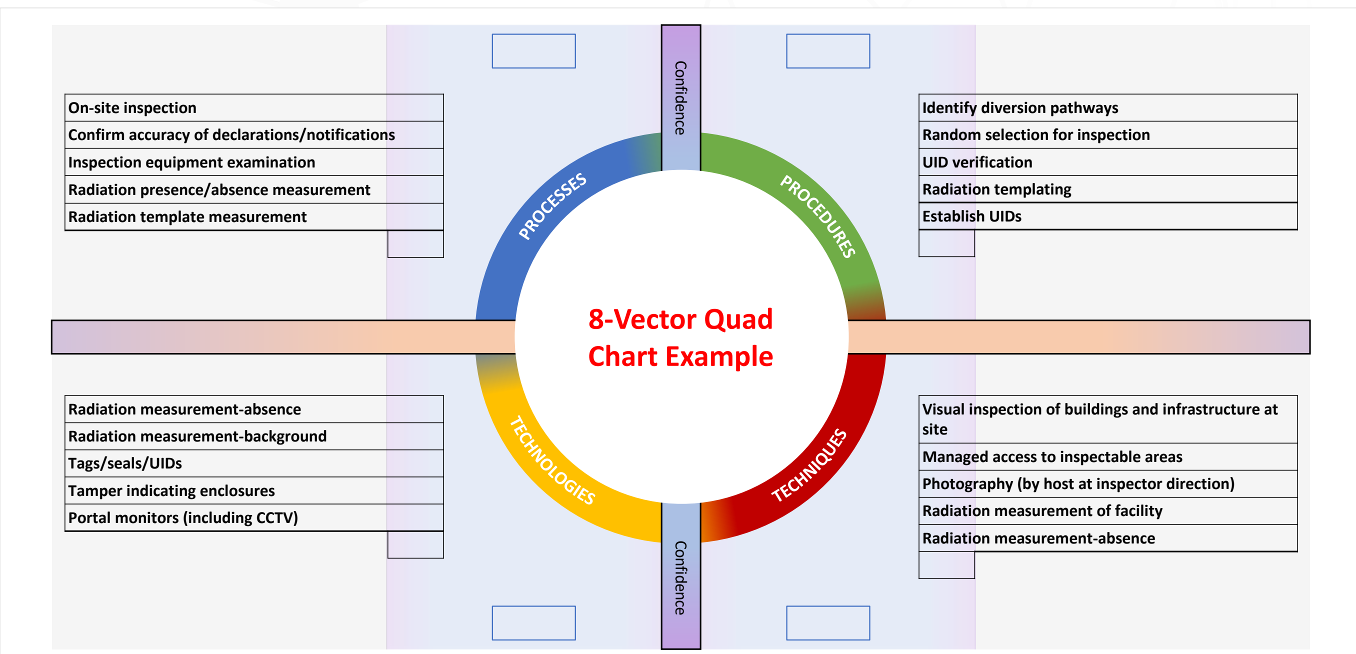
Both the Inspector and Host Task Groups emphasized the importance of building into any verification regime a mechanism for identifying anomalies that arise during the conduct of verification activities and resolving disputes over compliance. Good faith lapses in treaty implementation should be expected for many reasons: the amount of data to be provided in declarations, the long time period in which treaty implementation is likely to occur, the ongoing operation and maintenance of nuclear facilities and warheads, and any number of other bureaucratic and personnel lapses. An effective dispute resolution mechanism allows for more effective implementation of monitoring and inspection activities and provides a bridge linking the shared perspectives of inspectors and hosts.

Table 3: Examples of Managed Access
• Use of specially designated areas for some inspection activities • Authorization for specified activities to take place outside of inspectors' field of view • Restrictions on what inspectors can observe, from what locations, for how long, and by how many inspectors • Permitted use of shrouds, covers, and other means to protect sensitive information • Equipment to be used only by hosts at request of inspectors • Restrictions on direct physical contact with treaty-limited items • Inspectors escorted at all times

Section III: Thinking about Monitoring and Inspection Options—PPTT

During Phase III, the Partnership continued to assess and refine the IPNDV verification toolkit, that is, the set of declarations and monitoring and inspection PPTT identified in earlier phases.[4] The Partnership made an important step forward in organizing and visualizing the different monitoring and inspection options and the relationships among them. This approach, outlined in Figure 2, utilizes a "Quad Chart" that categorizes and links different PPTT at different phases of the dismantlement process. It also began to explore how these Quad Charts could be used in a more systematic manner to analyze and weigh trade-offs among PPTT options in the design and implementation of a nuclear disarmament verification regime.[5]

Figure 2: 8-Vector Quad Chart Example



4 For a full description of the IPNDV elements of the IPNDV verification toolkit see "Verification of Nuclear Disarmament: Insights from a Decade of the International Partnership for Nuclear Disarmament Verification", June 2024.

5 For a more complete discussion of the Quad Chart approach, see "IPNDV Phase III Quad Chart Report," December 2025.

The Basic Approach

By using these Quad Charts, the specific verification PPTT available for a given dismantlement step are binned in their appropriate baskets highlighting the relationships among these sets of PPTT. The *Processes* quadrant shows activities needed to achieve verification objectives in a specific situation. The *Procedures* quadrant shows the ways that processes are to be accomplished. The *Technologies* quadrant shows technologies necessary to fulfill the needs of the procedures. Finally, the *Techniques* quadrant identifies operating manuals, user guides, handbooks, checklists and other documents necessary to operate the technologies listed and implement other procedures.

In addition to providing a better means to visualize the PPTT options, the Quad Chart approach has other important advantages. By grouping together comparable monitoring and inspection activities, it highlights the relationships among PPTT and provides a basis to discuss the status and readiness of specific PPTT. In so doing, it also helps identify gaps to focus future work and capability development.

Using the Quad Charts to Assess Trade-offs and Choices

The Partnership also began to explore the more rigorous use of the Quad Charts as an analytic tool to assess:

- The relative contributions of different PPTT to achieving the specific verification objectives in a given scenario/situation such as verification of inter-site movement of Treaty-accountable items (TAIs)
- The relative importance of the different baskets of PPTT (e.g., processes compared to technologies) for achieving verification objectives
- The trade-offs between PPTT and across the broad PPTT quadrants in a given scenario
- The impact of "what if" situations in which one or another preferred PPTT might no longer be usable

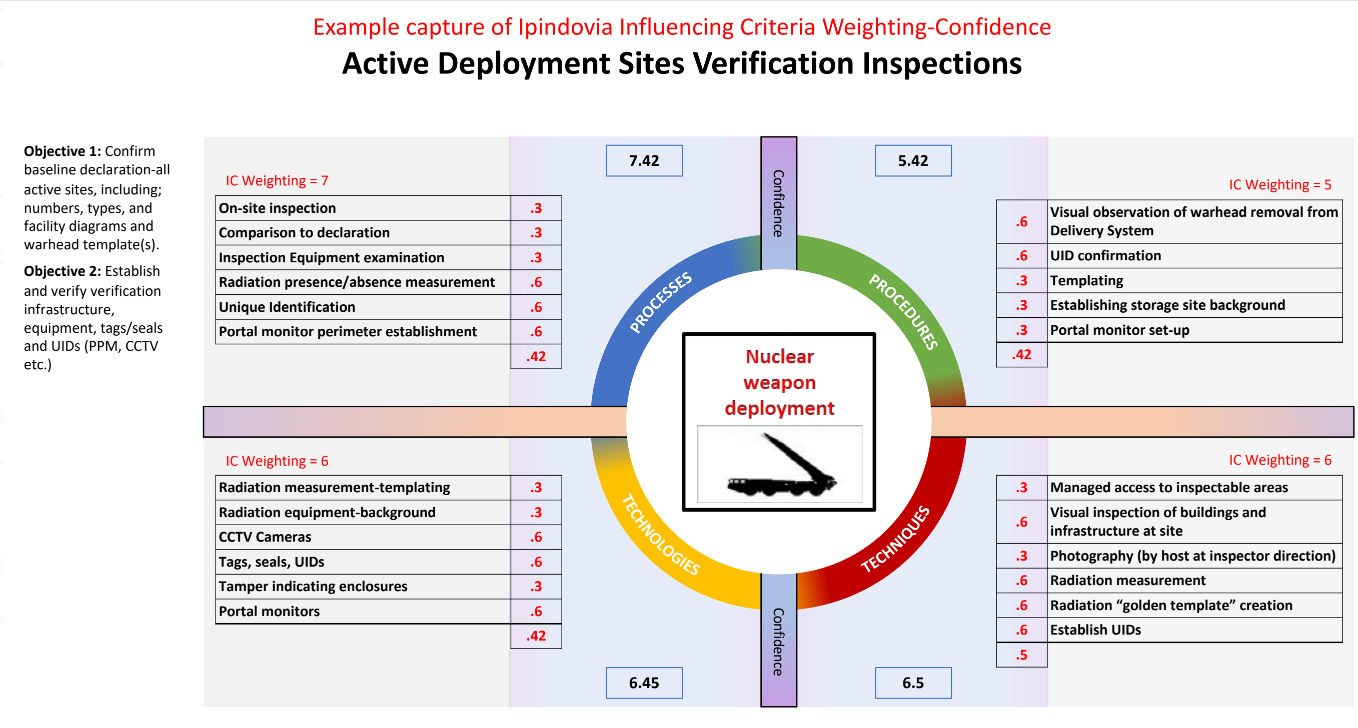
Specifically, two mini-exercises carried out during the June 2025 IPNDV Oslo Working Group meeting applied the Quad Chart approach in a scenario involving verification of the transport of containerized nuclear warheads. To set the stage, participants were given a set of "influencing criteria" that defined the overall verification context within which specific sets of PPTT would be implemented (e.g., the size/complexity of the Partner's nuclear weapons enterprise (NWE); familiarity with the PPTT, including whether they are modern, readily available, and understood; and experience/time of treaty implementation). Then, participants were asked:

- To place values on the contribution of specific monitoring and inspection options in each quadrant to achieving the verification objectives of that scenario—and to explain their reasoning
- To consider how their rankings of the specific PPTT could change in the event of one or more unexpected "what if" events, e.g., the unavailability of a specific monitoring technology because of a technical failure

Afterwards, by combining the average for all the PPTT in a given quadrant and the average for the influencing criteria, an overall illustrative ranking for the contribution of each quadrant to achieving the specified verification objective was derived.

Using the example of inspections at an active deployment site, Figure 3 illustrates how this process allows analysis of the relative importance of different PPTT and of individual quadrants, all in light of influencing criteria. For example, for the "processes" quadrant, the IC weighting is 7. The relative importance of specific PPTT is .3, .3, .3, .6, .6, .6, .3 and the average ranking of PPTT for "processes" is .42. Adding 7 and .42, the relative overall ranking for the "processes" quadrant is 7.42.

Figure 3: Active Deployments Sites Verification Inspection Example



The mini-exercises and the discussion that followed highlighted the value of this type of more rigorous analysis using the Quad Chart approach in a manner consistent with Bayesian analytic techniques. It can foster a discussion of the relative rankings of different PPTT options in building verification confidence in a specific verification situation, the ways in which different options build on and relate to each other, what may change those rankings, and of relative overall weightings among PPTT in a given scenario/situation. In addition, by combining the values of all four quadrants, this approach offers a starting point to assess overall verification confidence for that verification scenario/situation in light of available PPTT options.

Section IV: Verification of Limitations of Nuclear Warheads

The LWG's scenario posited that a nuclear-armed state, Ipindovia, agrees to limit the size of its arsenal to no more than 500 nuclear warheads for a 20-year period. Verification requires confirming both the accuracy of the initial declaration of 500 nuclear warheads and ongoing compliance with that agreed cap. This section briefly summarizes insights from the group's work in four selected areas: the unique dimensions of verification of limitations; potential diversion pathways involving activities at declared, formerly declared, and undeclared nuclear weapons facilities (including both former nuclear weapons facilities no longer required to be declared under an agreement and illicit facilities); and the use of Portal Monitoring (PM) as a monitoring and inspection tool (carried out in cooperation with the Technology Track).[6]

Unique Dimensions of Verification of Limitations on Nuclear Warheads

Verification of the maintenance of a nuclear arsenal at a given limit focuses on the post-reduction phase in which compliance with the posited 500-warhead cap would need to be continuously confirmed. In so doing, the verification challenge becomes to confirm the continuing absence of nuclear warheads over the treaty's central limit. Confirming absence is fundamentally shaped, moreover, by the fact that the parties to a limitations agreement continue to operate an active nuclear weapons program. There will be a steady flow of nuclear warheads and/or components among assembly/disassembly, storage, and deployment sites. The ongoing refurbishment of existing nuclear warheads adds special complexity by making it harder to distinguish legitimate maintenance from covert remanufacturing and requiring effective monitoring of refurbishment cycles to ensure that new weapons are not being produced. Ongoing nuclear weapons related research poses similar challenges.

[6] For a full description of the work of the LWG, see "Report of the Limitations Working Group," December 2025.

These unique dimensions led the working group to propose a new concept of "running knowledge"—defined as a persistent, verifiable understanding of a state's nuclear arsenal—as a central objective. They also underlined the importance of developing a verification framework that "holds inspectable items at risk," which emphasizes risk analysis to determine the priorities to be placed on the use of monitoring and inspection resources.

PERSPECTIVES FROM THE CO-CHAIRS OF THE LIMITATIONS WORKING GROUP

IPNDV's many years of work on nuclear disarmament verification has demonstrated that such verification is a complex challenge; however, verification can be carried out satisfactorily by well-prepared teams of inspectors—including if the inspectors are nationals of non–nuclear-weapons states. The LWG has shown that this principle also applies to the special case of verifying an upper limit over time on the number of warheads.

Nuclear arms control treaties that limit warhead numbers place additional security and operational restrictions on the inspectors. These restrictions are primarily due to the fact that some deployed forces will not always be available for inspection (e.g., nuclear missile submarines at sea) and time sensitivities of warhead movements. However, the LWG has shown that key focal points and locations in the "life cycle of a warhead" can be used to obtain sufficient confidence in overall treaty compliance. In turn for long-duration treaties, the accumulated knowledge resulting from a growing number of inspections over time increases the confidence in the verification assessments.

The unique challenges occurring when only low numbers of nuclear warheads remain is a topic not yet investigated. Among relevant questions would be the timelines to zero warheads, shifts in deterrence dynamics, and prioritization of dismantlement sequencing. Another important issue is to evaluate how new technologies such as AI, machine learning, and blockchain-based data validation could affect verification processes, inspector workflows, and diversion risks. The verification of warhead and delivery system changes has been discussed but not thoroughly explored and should be considered an important inclusion to future work on nuclear disarmament verification.

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. Practical exercises, something the LWG used extensively, are valuable tools for highlighting both challenges and opportunities related to nuclear disarmament verification, and they allow for extensive testing of various verification procedures and technologies.

Detecting Potential Diversion Pathways

Potential diversion pathways identified by the LWG's analysis include retaining excess nuclear warheads/ components at declared sites (including moving them between locations), repurposing formerly declared nuclear weapons facilities for production of non-declared nuclear warheads, and the establishment of undeclared production or assembly facilities.[7] Former nuclear facilities, those that were no longer part of a state's NWE at the entry into force of an agreement, continue to merit interest of an inspectorate, given their prior functions. The requirements of an agreement may require destruction of specific nuclear weapons infrastructure (e.g., silos and control centers at an intercontinental ballistic missile [ICBM base]). But such facilities still may have some dormant infrastructure (e.g., utilities, storage, or security features). In addition, unless specifically provided for in an agreement, these sites would not be subject to persistent surveillance and access by inspectors. These types of facilities are the primary reason that a challenge-type inspection be a part of any robust verification regime.

Identification of observable indicators is essential to detect attempted diversion. Indicators would vary depending on whether diversion involved a declared, formerly declared, or undeclared nuclear weapons site and the specific practices that a diverting country might use. Based on those indicators, tailored packages of layered and integrated monitoring and inspection PPTT can be identified to reduce diversion opportunity and increase detection probability. This is why the verification regime in a given agreement is bespoke. The configuration of the regime depends on the Treaty Central Objectives discussed in Section II above. The goal should be a clearer mapping of all three elements of diversion pathways, observable indicators, and PPTT packages. The technical and

operational limitations of detecting and deterring diversion, however, increase as the focus shifts from declared to undeclared sites.[8] At the same time, the relative importance of challenge inspections and complementary national and multilateral technical means increases.

Portal Monitoring as a Verification Tool

The LWG in cooperation with the Technology Track also undertook a more in-depth assessment of PM of treaty-related sites and other locations. PM uses measurements from strategically placed sensors to record the entry or egress of TAIs. These sensors may be actively managed by inspectors or operated remotely, with only periodic data checking. PM offers a tool to maintain chain-of custody over such items and to hold at-risk prohibited host activities when no inspectors are present. Across the different IPNDV verification scenarios, PM can contribute to building verification confidence. Using PM was identified as a key verification option in the limitations scenario and also figures prominently in the overall IPNDV verification toolkit. With regard

[7] These diversion pathways also were identified in the work of the Reductions Working Group discussed below.

[8] As part of its analysis of observable diversion indicators, the LWG also evaluated using shielding to hide a nuclear warhead's radioactivity. It concluded that the release of particles cannot be totally obscured with competent use of appropriate instrumentation.

to specific applications, as the analysis sets out, PM uses three key determinations. Beginning from the inspecting entity's verification objectives, the first step is to define the area of interest at the facility/site to be monitored (and its perimeter). The next step is to select portal locations, that is, intentional declared openings in the perimeter boundary around that area. The third step is to decide on what sensor technology or suite of technologies to use based on what attributes of the TAI are to be measured and verified to achieve given technical objectives.

Many options exist for sensor technologies to support PM (Table 4). Which technology to choose will depend on the objectives of the inspecting entity, the sensitivities of the host, what is permitted under the agreement, and the operations, activities, and items that are taking place within the specific site perimeter. Other considerations include balancing use of autonomous systems both during and outside of in-person inspections, avoiding the collection of too much data, managing false alarms, accounting for shielding material or container type on detection probabilities, avoiding revealing sensitive information about a TAI, transferring data to the inspecting entity, and integrating PM with other monitoring and inspection activities in an overall verification strategy.

Table 4: Some PM Sensor Technology Options

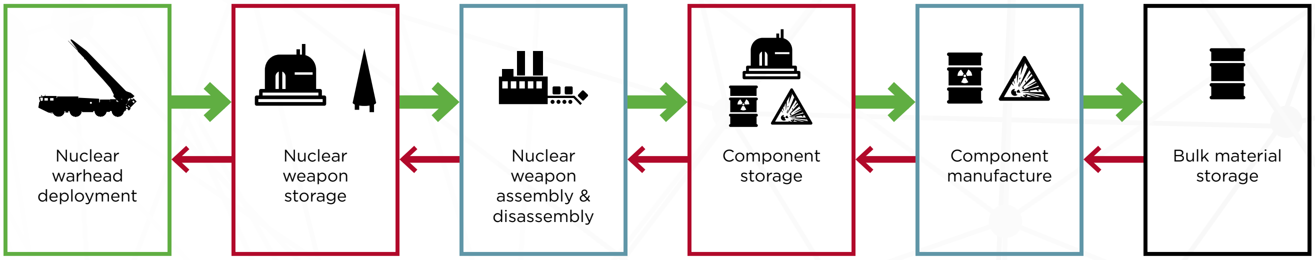
- Radiation detection
- Vehicle scanners with radiography to inspect spatial details of contents
- Break beams
- Weight or motion sensors
- Automated unique identifier (UID) readers with container with emitting UIDs

The IPNDV verification toolkit contains strong monitoring and inspection building blocks, as confirmed in exercises both by the limitations and other working groups. Effective verification, however, will depend on how those tools are sequenced, resourced, and paired within a broader verification approach. In that regard, the group suggested, one particular area to explore is what it termed "verification by design" in which verification measures could be embedded into a purpose-built facility for conducting verification activities. However, practical considerations like cost and complexity of construction would likely result instead in the creation of dedicated areas in existing facilities for conducting such activities. This concept would reduce the burden on inspectors and hosts, while strengthening overall verification effectiveness.

Section V: Verification of Reductions to Zero

Building on the earlier analysis of verification of reductions of nuclear weapons from 1,000 to 500 deployed nuclear warheads, the Reductions Working Group focused from 2022–2025 on a scenario of reductions from 500 to zero deployed nuclear warheads. This work included insights regarding the elements and importance of a systems approach; possible ways to divert, retain, or produce nuclear warheads/components in violation of an agreement referred to as diversion pathways; the effectiveness of the IPNDV verification toolkit in deterring the most credible diversion pathways through the risk of detection; and possible principles for the design and implementation of a verification regime.[9]

Figure 4: Subsystems in the Ipindovia Reductions Scenario
(Green arrows represent main flow of items during reductions)



[9] See, "Report of the Reductions Working Group," December 2025.

The Importance of a Systems Approach

A systems approach to verification, as defined by the Reductions Working Group, requires a comprehensive description of the supporting basing infrastructure, and operational practices and activities to include maintenance and refurbishment of permitted nuclear deployments. This description serves to define the elements of a state's NWE at which TAIs could be located and that would need to be captured under a nuclear disarmament agreement. This in turn provides the necessary foundation for making decisions about how to allocate monitoring and inspection resources to confirm compliance with treaty obligations. Equally important, an understanding of the NWE is essential to making use of PPTT options to verify the absence of undeclared retention or production of nuclear warheads in violation of an agreement.

PERSPECTIVES FROM THE CO-CHAIRS OF THE REDUCTIONS WORKING GROUP

For the Partnership, the technical and diplomatic consultations, along with input from both nuclear-armed and non–nuclear-armed states, are essential in building a shared understanding of the complex dimensions of nuclear disarmament verification (NDV). Although nuclear weapons states bring experience from their NWE and some from arms control and disarmament negotiations and agreements, many non-nuclear weapons states have extensive experience with nuclear safeguards approaches, inspections, and technologies. Both sets of experience are valuable to discuss the relevant questions of NDV: Which specific treaty-related activities must be verified, how to achieve credible verification, and what allowances can be made to remain consistent with non-proliferation obligations.

A systems approach allows for the consideration of a state's nuclear weapons related infrastructure and related technical capabilities as a whole, with particular emphasis on how to verify that the NWE operates consistent with treaty obligations. Understanding how this enterprise operates—in our working group in a reductions scenario—is the foundation of detecting undeclared activities, whether retention of nuclear warheads or undeclared production of nuclear warheads. This requires identifying potential diversion pathways and countering them through specific monitoring and inspection PPTT, drawn from an overall verification toolkit, to establish a credible risk of detection.

This three-layered approach—systems description, analysis of diversion pathways, and application of a tailored set of PPTT—creates the flexibility to adapt and strengthen the verification toolkit when new insights, technologies, or situations emerge. It can be used to distill essential elements for verification of future treaties.

Looking ahead, IPNDV has many opportunities for further exploration. Our goal should be to continue identifying, assessing, and refining our toolkit of explainable, adjustable, and comprehensive verification measures to foster confidence that nuclear disarmament obligations are being met. Equally important is outreach to non-participating states, ensuring that IPNDV's work is widely understood and inclusive.

Identifying and Evaluating Potential Diversion Pathways in a Reductions to Zero Scenario

The Reductions Working Group identified three broad categories of diversion pathways: first, diversion from within the NWE of one or more nuclear warheads to be dismantled or of components therefrom after dismantlement; second, retention of undeclared nuclear warheads, either within treaty-accountable facilities or at an undeclared site; and third, undeclared production of nuclear warheads, again either within treaty-accountable facilities or at an undeclared site.

However, the relative attractiveness of any one of these potential pathways would depend heavily on the payoffs of diversion, the complexity and ease of implementing a potential diversion pathway, and the risk of detection based on the robustness of verification. In addition, the group's discussion also suggested two other important considerations for a potential diverting country: the time factor (gradually declining numbers of nuclear warheads and associated facilities) and the potentially changing attractiveness of specific diversion pathways when approaching zero.

With these considerations in mind, the following potential diversion pathways stood out:

- Swap nuclear warheads with simulated nuclear warheads—from delivery systems, in storage containers, or during dismantlement
- Divert nuclear warheads during transport within or between sites
- Retain undeclared nuclear warheads
- Undeclared production of nuclear warheads at a declared or undeclared production facility.

Supporting each of these diversion pathways are more specific accompanying nodes of activity that would need to be successfully carried out (see Table 5). Such nodes of activity provide opportunities for detecting attempted diversion by the verification regime. Depending on the specific diversion pathway and its accompanying activities, diversion may also require successful spoofing or tampering with monitoring and inspection technologies, as discussed below in the work of the Technology Track.

Table 5: Illustration of Diversion Pathway Nodes

Diversion Pathway	Examples of Nodes of Activity
Retain undeclared warheads	• Falsify baseline declaration required at entry into force of agreement • Tamper with PM equipment • Limit inspection access • Use simulated warhead or "shell game" with "display" warhead

Deterring Diversion by the Risk of Detection—Insights from Mini-Exercises

In light of the preceding analysis of potential diversion pathways, the Reductions Working Group conducted a series of half day mini-exercises. These mini-exercises provided additional specific insights regarding the process of diversion from the perspectives respectively of a potential diverting country and of an inspecting entity.[10] More broadly,

[10] For a complete discussion, see "Report of the Reductions Working Group," December 2025.

the mini-exercises highlighted that diversion is a dynamic process in which the payoffs, complexity, and risks of diversion will be shaped by the actions of the inspecting entity. Successful diversion also is not a one-time event. It requires a series of choices by the diverting country as well as successful deception over time. Thus, for the inspecting entity, any strategy to deter diversion by the risk of detection needs to be a dynamic one that adapts over time.

At the same time, the mini-exercises served as a means to test the expected effectiveness of the verification toolkit—declarations and notifications, on-site inspections, and technical monitoring PPTT—to deter diversion by the risk of detection in the reductions to zero scenario. Together, they confirmed that the set of PPTT should provide a robust set of options to detect and deter diversion. At the same time, this work highlighted a number of other insights about effective nuclear disarmament verification, some of which are noted in Table 6.

Table 6: Verification Insights from the Mini-Exercises
• Comprehensive declarations and notifications are the verification bedrock
• Robust UIDs, tags, and tamper-indicating seals are critical for ensuring chain of custody
• Radiation measurements are best used where they provide the greatest added value in strengthening or restoring chain of custody
• Remote monitoring is essential but many strategy questions remain for its use
• More thinking is needed about close-out, formerly declared facility, and challenge inspections (including at former nuclear facilities) to increase the risk of detecting undeclared retention or production of nuclear warheads
• National and multilateral technical means are an essential backup for detecting undeclared retention or production

Principles for the Design and Implementation of Verification Regimes

The Reductions Working Group's analysis also suggested a number of principles to be taken into account in the design or implementation of a nuclear disarmament verification regime. Some of these principles addressed monitoring and inspection means (e.g., the importance of having two layers of verification for each verification objective or the importance of robust baseline inspections as the foundation for ongoing verification). Others had more to do with the inspection planning process and the allocation of resources provided by an agreement (e.g., the need for a comprehensive understanding of the NWE in a treaty party and normal operations to provide a background against which to detect anomalous behavior). Still others focused on the importance of integrating in-country monitoring and inspection activities with out-of-country national and multilateral technical means.

Section VI: Refining Cross-Cutting Verification Concepts

The Concepts Working Group carried forward the IPNDV's exploration of concepts to guide the design and implementation of nuclear disarmament verification regimes. Its work focused on four main areas: confidence and trust in nuclear disarmament verification, phased irreversibility in nuclear disarmament, verification of the disposition of SNM from dismantled nuclear warheads (Step 14), and elements of verification strategy.

Confidence and Trust in Nuclear Disarmament Verification

In its analysis of building confidence that parties are fully implementing their obligations under a nuclear disarmament agreement, the Concepts Working Group explored a distinction between confidence and trust. Confidence is an evidence-based assessment based on the data provided by the monitoring and inspection activities carried out by the inspection entity; trust is a more personal, subjective assessment made by individuals. Both dimensions are present in nuclear disarmament verification.

Within the framework provided by this distinction, the design and implementation of a verification regime needs to address a number of elements that will influence overall verification confidence. These include confidence in the effective working of the specific verification mechanisms, from monitoring and inspections to data processing and storage; the human factor, including possible personal subjectivity and bias; and verification practicalities, that is, resource constraints that impact monitoring and inspection activities and require compromises and trade-offs. At the same time, the analysis identified ways to address these elements and bolster confidence, from bias mitigation strategies to using random selection methods over time.

The group's work acknowledged that absolute, 100% confidence in verification is unattainable. The aim should be to balance the above considerations in a way that achieves a "sufficient" level of confidence. In that regard, it also is important to explore further how to measure the contribution of specific PPTT to verification confidence. The Partners developed the Quad Chart Bayesian analysis tool to do this. Such efforts could discover ways to develop illustrative metrics or indicators of "sufficient confidence" in an overall verification regime. In the final analysis, however, "sufficient confidence" will be a judgment made by the parties to any nuclear disarmament agreement.

In turn, while difficult to influence or operationalize, trust is critical to a successful nuclear disarmament process. Ultimately, trust is personal to an individual even if influenced by external factors and the inter-personal relationships of leaders. However, as a general rule, effective verification that leads to high confidence assessments that other parties are in compliance with their nuclear disarmament obligations should foster trust.

Phased Irreversibility in Nuclear Disarmament

The concept of irreversibility, the group's analysis stressed, is central to the credible pursuit and maintenance of a world free of nuclear weapons. However, given the long timeline required to dismantle existing nuclear arsenals, to dispose of the still-classified fissile material from dismantled nuclear warheads, and the existence of latent capabilities to make nuclear weapons even after nuclear disarmament, there is not one final, conclusive end-state of absolute irreversibility. Instead, the Concepts Working Group's analysis suggested that it is better to think in terms of a spectrum of increasingly comprehensive levels of irreversibility, or what can be called phased irreversibility.[11]

PERSPECTIVES FROM THE CO-CHAIRS OF THE CONCEPTS WORKING GROUP

Verification of nuclear disarmament is not only a technical challenge, but also a practical and conceptual one. In Phase III, the Concepts Working Group addressed a number of such conceptual issues that affect nuclear weapons dismantlement in both the reductions and limitations scenarios. Issues included how to derive confidence in verification results, elements of a verification strategy, logistics issues in implementing verification, and verification of the disposition of SNM from dismantled nuclear warheads.

It is especially valuable to use in-person exercises as a way to refine and test analytic concepts. By way of example, the German-French Nuclear Disarmament Verification (NuDiVe) exercises of 2019 and 2022 tested the concepts developed in Phases I and II for verification of dismantling nuclear warheads. The conceptual work on verification of disposition, set out in this section, should be so tested and refined if necessary.

Many conceptual areas merit additional exploration. These elements include how verification needs to be adjusted as a state approaches zero nuclear weapons, including whether it requires more or less verification? Given how much data will be generated both before, during, and after verification activities, one needs to explore secure data storage methods, and how emerging technologies,

continued on page 25

[11] See "Phased Irreversibility in Nuclear Disarmament," December 2025.

Perspectives from the Co-Chairs of the Concepts Working Group (continued)

namely AI and machine learning, may be used to assist in data analysis. Moreover, given the heavy reliance on technology as well as data storage methods, cyber security and defense merits further review. The establishment of verification indicators, which support technology selection, inspection methods, compliance determination and ultimate confidence in inspection results, will be important to ensure consistency moving forward. Lastly, the impact of human factors in verification, including how diversity and bias with respect to inspection team selection and composition affects compliance assessments, should be examined further.

A key takeaway from Phase III is that sufficient capacity is paramount to implementing each step of the disarmament process. Even a single bottleneck can lead to the excessive accumulation of stored warheads or their components as well as decades of delays. Both of which can increase potential diversion risks and erode the credibility of the regime.

In addition, Phase III again demonstrated the importance of ensuring that work on nuclear disarmament verification remains a process of multilateral cooperation among various subject matter experts, including scientists, nuclear non-proliferation policy experts, and nuclear weapons specialists from both nuclear-armed and non–nuclear-armed states. This ensures a well-rounded consideration of all the factors affecting nuclear disarmament verification, and brings to bear the greatest set of minds, ideas, and solutions to address the complex yet achievable challenge of creating a credible and effective verification capability.

In today's more dangerous world, the IPNDV offers a valuable non-political approach to making tangible progress in the verification of nuclear disarmament. It builds greater trust within the arms control community as this technical and scientific collaboration among nuclear-armed and non–nuclear-armed states identifies and tests credible solutions to the challenge of verification of nuclear weapons dismantlement. This work will hopefully help achieve one day the objective of a world free of nuclear weapons.

More specifically, during the gradual elimination of nuclear weapons, each specific step in that process contributes to confidence in irreversibility, from the verified dismantlement of nuclear warheads and the disposition of the SNM from those warheads to the elimination of nuclear delivery systems, fissile material production facilities, and personnel. Other ancillary changes also would build confidence in irreversibility (e.g., changes in defense doctrine, budgets, education, and training). Throughout the nuclear disarmament process and afterwards, there would be rigorous verification to build confidence that any reversal would be detected in a timely fashion. Together these actions would make it too technically, financially, politically, and militarily costly to reconstitute a previously eliminated nuclear weapons capability. The result would be adequate rather than absolute irreversibility.

Verification of Disposition (Step 14)

The verification of disposition of nuclear weapons components presents numerous complexities. Disposition of the SNM components could occur in a variety of ways that may involve chemical processes and down-blending of those components such that the SNM is transformed to bulk material with different geometric, chemical, and isotopic properties. When the SNM also changes form in a process not visible to inspectors, unique implications surface for the verification of disposition. The following concept for the verification of disposition of nuclear warhead SNM components attempts to address these unique issues. In particular, although it is difficult to generalize the verification of SNM disposition due to the various processes and facilities that may be involved, the extensive work done on verifying nuclear warhead dismantlement provides much to draw from in considering how verification of disposition may occur.

More specifically, in the IPNDV scenario, the disposition process would be treated as a black box in which inspectors would not have access to the disposition area during processing activities. Perimeter monitoring combined with absence measurements would verify that no unaccounted SNM enters or leaves the process area. Tamper-indicating chain-of-custody technologies would be used on containers with dismantled SNM components entering the disposition area and to ensure the integrity of TAIs entering the disposition process. Prior to disposition activities, inspectors may have access to the dedicated disposition area to confirm that no potential diversion pathways exist. However, if nuclear material is present in the process area for blending during disposition operations, there would be no need to verify absence during this inspection. After concluding disposition activities, inspectors would again check the integrity of the dedicated disposition area and also take radiation measurements to confirm that material from dismantled nuclear warheads was no longer present. This absence verification may be complicated by radioactive waste streams or unused down-blending materials that may be present in the processing area. Given that the processed material may have lost most or all of its sensitive characteristics at this stage, more detailed analysis could be undertaken post-processing to build verification confidence. There would likely be increased emphasis on verifying that the resulting disposition material has characteristics that confirm TAIs have been processed if nuclear material inputs and waste streams make absence verification challenging during earlier steps.

Thinking About a Verification Strategy

Since its inception, the IPNDV has used analyses and exercises to illuminate the trade-offs and choices inherent in the design and implementation of a nuclear disarmament verification regime. In parallel with the new Quad Chart approach for exploring the contributions of specific PPTT in different scenarios and analyzing options for use of PM, the Concepts Working Group also carried forward this work stream by analyzing verification strategies

(Table 7).[12] In so doing, it focused on a series of topics, from the generic elements of any verification regime; use of a systems approach; inspection quotas; logistical arrangements, including the advantages and disadvantages of using dedicated areas in existing facilities/sites for carrying out treaty-related activities; and development of an illustrative basic verification strategy for making the choices and trade-offs among the PPTT within the IPNDV toolkit.

Table 7: Some Considerations for a Verification Strategy

- Begin from a systems approach that describes the full NWE of parties to an agreement
- Avoid unnecessary and repetitive verification activities, which do not provide significant additional confidence
- Focus on proven and robust chain-of-custody technologies
- Reduce or eliminate use of verification technologies or techniques that are deemed difficult to accept by nuclear possessing states or that require use of highly intrusive technologies for a high amount of confidence
- Limit radiation measurements to situations in which they are most effective, efficient, and necessary
- Balance the need to assure the highest levels of safety, security, and non-proliferation and the need to achieve confidence in the verification activity

With regard specifically to verification strategy, the Concepts Working Group's analysis began by setting out a number of considerations or tests to guide the design and implementation of a notional verification regime. Based on those considerations, the analysis then proposed a specific strategy for further discussion. That strategy would rely most heavily on proven and robust chain-of-custody monitoring and inspection activities and technologies. It would use radiation measurement techniques primarily to restore confidence in the event of a breakdown of chain of custody or for other special circumstances (e.g., establishing provenance over non-deployed or retired nuclear warheads once they are initialized into the dismantlement stream). This analysis demonstrated that the proposed verification strategy could be applied across the 14-step model.

[12] See "Conceptual Elements of Potential Verification Strategies," December 2025.

Section VII: Advancing Understanding of Verification Technologies

During Phase III, the Technology Track continued its work on the role of technologies to support the verification of nuclear disarmament. In addition to its input to the development of a concept for verification of Step 14 disposition, the Technology Track carried forward its ongoing work on options for measuring the absence of SNM and/or HE; joined with the members of the Limitations Group in a deep-dive analysis of PM, as already discussed above; and in response to questions from the Reductions Working Group, explored the issue of the spoofing or tampering with monitoring technologies as part of a diversion strategy. Its members also once again organized measurement campaigns to demonstrate and test specific verification technologies and approaches.

Options for Absence Measurements

The Technology Track's analysis identified multiple technology options for confirming the absence of TAIs, whether nuclear warheads or the SNM or HE components from a dismantled nuclear warhead.[13]

Grouped into passive and active methods, as shown by Table 8, these technologies rely on different detection principles. For each, the Technology Track refined its analysis of the advantages and

Table 8: Options for Absence Measurements

Passive Method	Active Method	
• Passive Gamma Detection • Passive Gamma Imaging • Passive Neutron Counting • Passive Neutron Imaging • Muon Tomography	• Gamma/neutron Transmission • Active Multiplicity Counting • Active Fast Neutron Counting • X-ray Imaging • Nuclear Resonance Fluorescence	• Raman High Explosives Identification • NQR-Explosive Identification System • Fast/Thermal Neutron Interrogation System • Compton Backscattering Cameras • X-ray Computed Tomography

[13] See "Nuclear Disarmament Verification and Technology Options for Absence Measurement" IPNDV Tech Track Deliverable for Phase III.

disadvantages in terms of the time needed to set up the equipment and carry out a measurement; the verification value for confirming the absence of uranium, plutonium, or HE; the mobility of the equipment; whether the absence measurement would need to be confined to a limited area or could be used over a wider area; and the implication if multiple nuclear warheads are nearby.

A number of practical and technical considerations also were identified that need to be taken into account in the verification of absence. For example, depending on the specific option, the estimated set up and measurement time together frequently is up to several hours. Verification also is simpler for measurement of the absence of plutonium than the absence of uranium. In turn, the level of confidence provided by using these technologies depends not only on the intrinsic capabilities of the technologies, but also on the context of when and where they are used, and what other verification measures complement them.

The technology capabilities that apply to verifying absence, the Technology Track's analysis noted, are essentially identical to the ones used for verifying presence. However, the requirements of the equipment and the way the equipment is used may differ considerably, and lead to significantly different design choices. Verifying presence also is more likely to require using an information barrier to protect sensitive information.

Spoofing or Tampering with Verification Technologies

Spoofing or tampering with verification technologies is part of several diversion pathways identified by the IPNDV for cheating on a nuclear disarmament agreement. In response to questions from the Reductions Working Group, the Technology Track explored this issue in greater detail with a focus on the opportunities and challenges for spoofing or tampering with verification technologies.

A potential diverter will seek opportunities to exploit, for example, using available reactor-grade plutonium or other material to simulate a nuclear warhead or its SNM components, altering the environment in which measurements are made to impact the result, taking advantage of digital or internet-connected equipment (if present), or using shielding. Overall, it may be less difficult to spoof the absence of highly enriched uranium (HEU) than plutonium due to the high gamma-ray and neutron emission of plutonium.

However, a potential diverter also will encounter multiple technical and other challenges, for example, replicating certain SNM signatures with non-SNM materials may be difficult. Successful spoofing also will likely require that a fake item repeatedly spoof multiple layers of monitoring and inspection measures over an extended period of time as it becomes subject to possible repeated monitoring or inspection activities. In turn, attempted spoofing by using a simulated warhead may also create indicators of diversion (e.g., if it requires breaking standard operating procedures or as it comes to involve larger numbers of personnel in illicit activities and falsified paperwork). Or, a specific spoofing strategy may itself create indicators of potential diversion (e.g., using shielding to spoof the absence of a nuclear warhead).

Not least, the design and implementation of a monitoring regime and its specific equipment choices

PERSPECTIVES FROM THE CO-CHAIRS OF THE TECHNOLOGY TRACK

Through 10 years of IPNDV, we have come to understand that the international community has a significant set of technology options for nuclear disarmament verification. However, one of the complexities regarding verification technologies is to strike the right balance between the possibility of adding confidence by relying on more technologies and not adding unwarranted burdens on the conduct of monitoring and inspection activities as well as using limited resources effectively.

In terms of important remaining challenges, the verification of HEU remains an outstanding challenge in this space. Other remaining challenges relate to adapting existing technologies for use in nuclear disarmament verification, in particular to enable technologies to satisfy the certification and authentication criteria that is necessary from the host and inspector perspective, respectively.

One overarching takeaway from Phase III is that there continues to be value in this type of unique work between countries without nuclear weapons and countries with nuclear weapons. IPNDV was formed more than 10 years ago, and the world now is not as it was then. Yet, IPNDV participants continue to learn something new at every meeting—whether through scenario-based discussions, hands-on exercises, or technology demonstrations/measurement campaigns. All have been useful ways to make progress in this space and raise everyone's "nuclear disarmament verification IQ."

can anticipate and build-in treaty-based counters for attempted technology spoofing or tampering. Examples the Technology Track analysis explored include tamper-indicating tags and seals that increase the likelihood that tampering with containers holding TAIs or with monitoring equipment would be detected; data encryption and isolating monitoring devices from the internet lessens data vulnerabilities; providing for non-interrupted power supplies helps ensure continuity of operations of monitoring systems; and relying on equipment with minimum functionalities provides fewer opportunities for tampering.

Technology Measurement and Demonstration Campaigns

During Phase III, the members of the Technology Track again organized technology demonstrations and measurement campaigns (Table 9). Campaigns and demonstrations tested technologies for detecting the absence or presence of plutonium and HEU, the presence of HE, and for PM. In some cases, one Partner country hosted a group of countries to test their own technologies. In other cases, a single Partner country presented the results of its own analysis and testing. The results refined the IPNDV technology knowledge base.

Table 9: Technology Measurement Campaigns and Demonstrations

- Active Neutron Interrogation (Canada)
- Uranium Isotope Determination – BeCamp 2 (Belgium)
- Portal Monitoring (Hungary)
- Trusted Radiation Identification System (United States)

Section VIII: Elements of an Agenda for Future Work on Nuclear Disarmament Verification

Considerable progress has been made in realizing the IPNDV's original goal to identify technical and procedural challenges associated with the effective verification of future nuclear disarmament efforts and develop practical solutions to overcome those challenges. Based on that work, this section identifies possible elements for future work in four areas of nuclear disarmament verification:

- Concept development and refinement
- Technology assessment and testing
- Validation exercises
- Sustaining and building global capacity

This list is intended to be illustrative and not exclusive.

Concept Development and Refinement

During Phase III, the Partnership began exploring the idea of having dedicated disarmament facilities designed in a way to support inspection activities. Given the time, money, and regulatory hurdles that would have to be overcome, it almost certainly would be impractical to establish purpose-built sites for storage or dismantlement of TAIs under a nuclear disarmament agreement. However, creating *dedicated areas for carrying out treaty-mandated activities* within existing sites/facilities warrants additional conceptual development. By way of example, what would be the characteristics of a "plant-within-a plant," how might it be monitored, and what would be its payoffs and risks. This should be explored for a variety of activities including dismantlement of nuclear warheads, nuclear weapons delivery systems, nuclear weapons components, etc. Are there other examples of treaty-related activities that could be carried out using the plant-within-a plant concept?

A closely-related but more specific concept that was proposed is establishing a *segregated controlled area* where warheads subject to an agreement would be stored immediately after their transport between sites. Recognizing that individual states will have different nuclear enterprises, conceptual questions that warrant further exploration include how and

where to establish such areas, what limits should be placed on items introduced into it, what technical monitoring means could be used to monitor them, and how would the resulting monitoring data be stored and accessed during later inspections.

More broadly, the costs, risks, operational requirements, and practicalities of different options and strategies for *PM* as part of the creation of such dedicated areas or the preceding restrictions on TAI movement could be assessed in greater detail. Already identified options range from ad hoc use during specific inspections to permanent on-site PM presence, whether through remote systems or through on-site inspections. More specific questions concerning the detailed operations of such equipment, its relationship to other monitoring means, and countering possible tampering or spoofing should be explored.

Close-out inspections for bases and infrastructure that is no longer treaty-accountable and periodic *inspections at formerly declared facilities* both have been identified as important activities to increase the risk of detection of undeclared retention or production of nuclear weapons. Drawing on past experience with such inspections in other arms control agreements, it could address when and where to permit such inspections, their modalities, and their potential contributions in an overall verification regime.

The IPNDV has long identified the importance of challenge inspections to verification of the absence of undeclared activities in violation of a nuclear disarmament agreement. Phase III began to explore concepts for challenge inspections for deterring diversion by retention of undeclared nuclear weapons or undeclared production of nuclear warheads. Future concept development could focus on how to implement the principle identified by the IPNDV of "everything at risk at all times" in terms of *modalities, limitations, and utility of challenge inspections.* Again, this work could draw on the experience and lessons with challenge inspection provisions of existing agreements.

Prior work to define illustrative CONOPS to carry out specific nuclear disarmament verification tasks also could be carried forward. Together, such CONOPS provide essential background in thinking about the choices and trade-offs of inspection planning and monitoring technology development and implementation requirements.

The importance of credible and reliable *data management, data security, and data control* has repeatedly been raised during Phase III, including in exercises. A next step would be to identify more comprehensively the issues likely to arise in this area and to explore how best to address them. Questions include how to authenticate and protect data from inspections through ensuring access to earlier data in an ongoing multi-year inspections process to deciding what data will be made available and to whom. As part of this conceptual work, more detailed work could be carried out on the certification and authentication of monitoring and inspection equipment.

Future work also could explore other disposition options and their relative irreversibility beyond just down-blending for *disposition of SNM,* for example, vitrification followed by deep underground burial.

In its scenario-based approach, the IPNDV could consider still other scenarios. For example, it has yet to address the *verification of maintenance of a world with zero nuclear weapons.* Specifically, how to apply the IPNDV verification toolkit in this scenario, including how to adapt existing monitoring and inspection PPTT to achieve the specific verification objectives in the maintenance of zero nuclear weapons. Particular questions for analysis could include:

- How would baseline declarations and inspections change in this scenario?
- What would be the role and modalities of close-out inspections for sites formerly part of a state's NWE?
- What types of challenge inspections would be needed and what lessons can be drawn from those types of inspections in existing arms control regimes?
- What potential diversion or breakout pathways exist in a world without nuclear weapons and could the risk of diversion/breakout be increased?
- What additional types of monitoring and inspection measures might be added to the overall verification toolkit developed in Phases I–III, including, for example, environmental monitoring, national/multilateral technical means, and using AI?

Finally, while the IPNDV has focused on the dismantlement process as the most challenging aspect of nuclear disarmament, additional steps are on both the front-end and back-end of the development of nuclear weapons that could warrant further attention. With respect to the former, numerous steps need to be taken to convert uranium or plutonium into weapons-usable nuclear material. On the latter, additional steps are necessary to take the disposed nuclear material and place it into long-term storage where it is immobilized and unable to be used for nuclear weapons. Future work could identify additional steps to examine, which would build from experience of the non-nuclear weapons states that have mature peaceful civilian nuclear programs. Broadening the analytic scope in these ways would capture a wider range of verification challenges.

Technology Assessment and Testing

Technology assessment campaigns have been an essential feature of the IPNDV's shift from paper to practice in Phases II and III. Groups of countries have organized different campaigns, with one country hosting and others bringing specific technologies to demonstrate or test. Technologies for the detection of the presence or absence of plutonium have been central to this effort. Future technology assessment campaigns could carry forward this work on plutonium or they could turn to the greater challenge of detecting the presence or absence of HEU.

Carrying forward *technical analysis on the use of an information barrier system* to protect sensitive information during certain technical monitoring activities is another area for future technology assessment. At one level, this work could continue to refine understanding options for such systems' design, associated procedures, and operations, including what circumstances might not require using an information barrier (e.g., radiation measurement to confirm absence of SNM in a room or container). During Phase III, other possible opportunities were identified for using information barriers to permit verification-related measurements while protecting sensitive information (e.g., for verification of the weight of containers declared to contain nuclear warheads).

PERSPECTIVES FROM A CO-CHAIR OF THE TECHNOLOGY TRACK

Nuclear disarmament verification takes a lot of understanding of all the various nuances associated with nuclear science, but this is something in which both countries with nuclear weapons and countries without nuclear weapons have various levels of expertise. Additionally, being able to translate that technical information into something negotiators and policy personnel can understand can be hard to do. Experienced practitioners of nuclear disarmament verification are becoming fewer by the year, and conveying that knowledge is important so that future practitioners do not have to "reinvent" or re-learn the lessons from the past the hard way.

The most important technical challenge is verification of HEU. Other very important technical challenges are being able to authenticate data from verification equipment and trying to create a verification scheme that has a high level of confidence, but that is not overly intrusive or resource intensive. Having a way for the international community to discuss these issues is important for when the dialogue is started in earnest. For nuclear disarmament verification to be successful, all parties need to be knowledgeable.

The sustainability of the Partnership, or maybe the lack thereof, now is an open question. There is an international view that something needs to be done on the subject of nuclear disarmament verification. But there seems to be a lack of urgency. Thus, the willingness to continue to work in a format like IPNDV seems to be waning, particularly as the participants turn over. Additionally, the need to put actions into practice takes a lot of effort (time, resources, etc.) that many of the Partners currently do not have available. Nonetheless, the IPNDV has continued this long because the Partners consider nuclear disarmament verification an important conversation to keep engaging in.

Effective UIDs, tags, and tamper-indicating seals are critical to maintaining chain of custody over TAIs. Assessment of *innovative technologies for UIDs, tags, and seals* also could be part of future technology assessment. One example would be active tags and seals that monitor the integrity of a container and report when it has been sealed or opened. Another example would be UIDs or tags that could be read automatically when passing through a reader. Still another area to explore would be so-called "buddy tags" in which an external tag on a container is linked to an internal tag attached to the item inside with appropriate protection of sensitive information but in a manner that the external tag can be read to confirm the continued presence of the TAI in the container.

Another area for work would be to evaluate how new *emerging technologies* could affect monitoring processes, inspector activities, diversion risks, and verification planning and implementation. Examples include AI, machine learning, blockchain-based data validation, and remote fabrication detection.

To help highlight technology requirements and opportunities, technical experts could seek to *define an illustrative five-year technology assessment plan*. Such a plan could set out the most important outstanding technology development challenges related to nuclear disarmament verification, assess the state of play in meeting those developments, and then consider the pluses and minuses of giving priority to different initiatives. The process of discussing such a plan could be as important as any specific outcome.

Validation Exercises

An exercise on *verification of absence of nuclear warheads* would provide a means to test, refine, and generate insights regarding the elements of a notional challenge inspection regime. For example, one approach would first define those elements—authorization, modalities, timing, quotas, rights of inspectors—and provide them to teams composed of inspectors and host. Then, the exercise could focus on how the inspectors would seek to carry out a challenge inspection at a site suspected to have undeclared nuclear warheads and how the host would respond in such an inspection process. To the extent possible, this exercise and others should be carried out in-person in an environment that closely resembles real-world conditions as opposed to as a tabletop exercise.

An *inspection planning exercise* would be one way to explore the implications of a multi-state, multi-year, multi-item, multi-site inspection process under a nuclear reductions to zero disarmament agreement. This exercise would define the monitoring and inspection toolkit available to a multilateral inspection entity as well as the nuclear enterprises of three countries that were party to the agreement. Then a planning cell of the inspection entity would develop a plan for how to use that toolkit in multiple treaty parties over the course of a single treaty year. In so doing, it would be possible to explore and illuminate trade-offs and choices in what to monitor/inspect, how, when, and where.

A two-part Quad Chart mini-exercise on monitoring and inspection trade-offs, choices, and responses to "what if" events would build on earlier IPNDV mini-exercises. Delving deeper into the IPNDV Quad Chart approach, the first part of the exercise would illuminate the relative rankings and choices among monitoring and inspection PPTT for carrying out a given verification task (e.g., confirming no diversion from storage). In this part, as background, participants would be given a verification context (e.g., year of treaty implementation, technology

readiness level, and asked to define their preferred set of PPTT). The second part would posit a number of disruptive events that ruled out using one or another monitoring and inspection means, while asking participants how they would compensate for that change. The second part also could explore how changes in the verification context could impact their preferred set of PPTT.

Exercises to *test the implementation of specific PPTT* have already proved a valuable means to refine thinking about inspection activities, identify issues needing attention, and to strengthen overall understanding of the challenges of nuclear disarmament verification and ways to meet them. Given that warhead transportation has been identified as a particularly sensitive step, a future exercise could focus on that step but do so in a more realistic setting. In turn, another possible area would be inspections at formerly declared sites/facilities, including challenge-type inspections at former nuclear facilities that existed prior to the entry into force of an agreement. A different exercise could test the PPTT for verification of the disposition of SNM from dismantled nuclear warheads.

In light of the essential importance of chain of custody, a different mini-exercise could address *restoring chain of custody* over TAIs. Different breakdowns of chain of custody could be posited, from loss of technical monitoring at a storage site to repeated instances of possible tampering with tags and seals on containers with warheads being transported between sites. Possible inspector and host responses then would be explored.

Sustaining and Building Global Capacity

Through its mix of cooperative problem solving, encouraging national initiatives, technology demonstrations and campaigns, and outreach, the IPNDV has helped build global capacity for nuclear disarmament verification. It is essential to sustain that capacity. A continuation of these types of activities would be an important means both to build and sustain capacity. Some possible specific initiatives could include an in-person tabletop or on-site exercise sponsored and organized by a group of states, creation of communities of interests on specific verification topics, and, as already proposed, a new technology campaign. Earlier phases also made clear the value of on-site visits to former nuclear weapons sites and facilities as a means to build capacity.

The proposed Group of Scientific and Technical Experts (GSTE) on Nuclear Disarmament Verification, if established, also will help to build and sustain global capacity. Through the participation in the GSTE of Partner country experts and other engagement, its work can leverage and take advantage of the insights developed by the IPNDV over the past decade.

In addition, organizing an *annual meeting of stakeholders* in the field of nuclear disarmament verification would be one way to complement those broad thrusts. It would allow other organizations and entities working in this area (non-governmental, academia, etc.) to set out their projects and findings, while encouraging dialogue among them.

Learn more at www.IPNDV.org

The IPNDV website is home to numerous reports and educational resources that capture the knowledge and analysis produced by the Partnership over a decade of working group meetings, exercises, and technology demonstrations.

Reports and analysis

Dismantlement Interactive

Information about related initiatives

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 **visit www.ipndv.org**.

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