Monitoring Approaches to Support BWC Compliance

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Credits

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Executive Summary

The Biological Weapons Convention (BWC) remains the only WMD treaty without a formal verification mechanism. Within the context of renewed interest in BWC verification, this report explores the applicability of different possible approaches to verification and monitoring.

A known challenge to verification in the life sciences is the breadth of applications – and possible threats. In order to evaluate monitoring approaches, the report lays out a set of hypothetical scenarios, ranging in scale, scope, and technological sophistication. For each scenario, the report lays out the pathway to acquiring biological weapons and presents a set of observables: practical aspects such as technologies and activities that can be monitored.

Monitoring approaches

The report considers three sets of possible monitoring approaches: the BWC Confidence-Building Measures (CBMs), the Verification Experts Group (VEREX), and emerging technologies.

While the CBMs were adopted as a transparency measure, they can in theory capture up to half of the identified observables. However, those not captured include dual-use and defense-related activities. CBMs can support verification, but they rely on complete and correct submissions.

VEREX identified a broad set of verification measures that remain relevant today. However, they are broadly defined, and the real value – and challenges – for each would emerge once specific implementation details are decided. Integrating emerging technologies into its established frameworks offers a promising pathway for further discussions on strengthening the BWC.

Advances in genetic sequencing, microbial forensics, artificial intelligence and remote sensing have expanded both risks and monitoring opportunities. These can strengthen off-site monitoring, detect anomalies in patterns of research and production, and increase confidence in on-site identification and analysis.

Overall, compliance monitoring offers a spectrum of options, ranging from transparency and information exchange to legally binding processes and on-site investigations. Different methods will offer various levels of confidence, but perhaps at the cost of more intrusive practices. A layered system would be most effective, with more intrusive or resource-intensive verification techniques deployed only when specific concerns arise.

Recommendations

The report identifies a number of recommendations for BWC States Parties: supporting the CBM process; practicing and normalizing consultation and clarification; seeking greater understanding of confidence and uncertainties in verification; and discussing practical aspects of different verification measures; practicing verification in the field via exercises.

Political feasibility will ultimately drive decisions on compliance monitoring, but incremental, cooperative steps can build confidence and prepare the ground for future verification mechanisms.

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Chapter 1

Introduction

At present, the Biological Weapons Convention (BWC) has no formally established compliance mechanism. The convention relies on Confidence-Building Measures (CBMs), internal enforcement, and voluntary transparency by some States Parties through Article V consultations. In recent years, a new sense of urgency has energized discussion of compliance monitoring under the BWC, as well as broader measures to investigate the possible production or use of biological weapons. This is partly due to the emergence or maturation of relevant technologies, which include microbial forensics, genetic sequencing, machine learning, improvements in satellite imagery resolution and availability, and the increased availability of tools and sources for open-source intelligence (OSINT). Another factor is increased concern for the risks posed by biological weapons, raised both by the use of chemical weapons in Syria and in several high-profile targeted assassinations by state actors, and by the COVID-19 pandemic.

Almost 30 years ago, the Verification Experts Group (VEREX) report assessed that no single verification measure could effectively assess compliance, and that a combination of layered verification techniques would be required. This insight still holds true and was confirmed more recently by evaluations of recent experiences such as OPCW investigations in Syria[1] and of the progress made on key verification processes such as laboratory characterization of agents and microbial forensics.[2]

A core challenge to verification and monitoring in the BWC context is that many activities crucial to the production of biological weapons are inherently dual-use, and that it may be difficult to distinguish legitimate research or biodefense activities from a weapons program. Because of this, it is difficult to discuss practical and specific goals and targets for monitoring activities under the BWC.

This report outlines the findings of a 2-year project by VERTIC and King's College London. The project sought to evaluate potential monitoring approaches against a number of specific, detailed hypothetical proliferation scenarios, and it considered the impact of novel and emerging technologies on the matter. To do so, the project drew from methodologies used in nuclear non-proliferation, chief among them the Acquisition Path Analysis employed by the International Atomic Energy Organization (IAEA).

Methodology

The study's ultimate goal is to provide an informed evaluation of the feasibility of different possible approaches to verification and monitoring of the BWC, considering transparency measures, proposed verification methods, and emerging and novel technologies. This type of analysis needs to account for the specific types of activities, equipment and facilities (as well as other factors) that would be subject to monitoring – a significant challenge given the complexities of the life sciences field.

To do so, the research team first identified a number of specific proliferation scenarios that the analysis would focus on. The team then mapped possible pathways for acquisition of biological weapons, identifying specific capabilities, technologies and equipment. Finally, the team used these acquisition pathways

1 The use of reports to present the combined results from different techniques is covered in McLeish, C. & Moon, J.R. (2020).

2 Both the advancement in microbial forensics and the need for a broad set of techniques to support and confirm results of laboratory analysis are covered by Trapp, R. (2023).

to identify "observables", detailing facilities, equipment, activities and intangible aspects that would be relevant to verification and monitoring activities.

The observables provided a tangible, practical benchmark to examine the potential of different approaches to monitoring under the BWC.

Scenarios

The breadth and diversity of biological activities across industry, medical research and other fields makes it extremely challenging to map activities of all possible kinds, and trying to do so would have gone beyond the scope and means of this study. Using hypothetical scenarios allowed the team to narrow down the analysis. The team settled on three scenarios:

- Scenario A – a large and technologically mature program, with a number of facilities;
- Scenario B – a small and sophisticated program focusing on novel technologies (this scenario was further divided into two sub-scenarios, focusing respectively on the R&D and the production aspects);
- Scenario C – a small, highly clandestine program using widely available, conventional technologies.

The chosen scenarios aim to reflect the concerns of the international community, by modelling both known cases of biological weapons development,[3] and prospective risks that the community has debated in recent years.

In order to develop the scenarios, the team set up a template containing key questions about the hypothetical bioweapons program under considerations – ranging from policy goals and intended targets, to the types of agents pursued, to specific facilities, technologies, and organizational elements. This guaranteed that the scenarios would take all the relevant factors into consideration, and that the different scenarios would be developed to similar depths and levels of detail. The template used to develop the scenarios for this study can be found in Annex I.

Acquisition Pathways and Observables

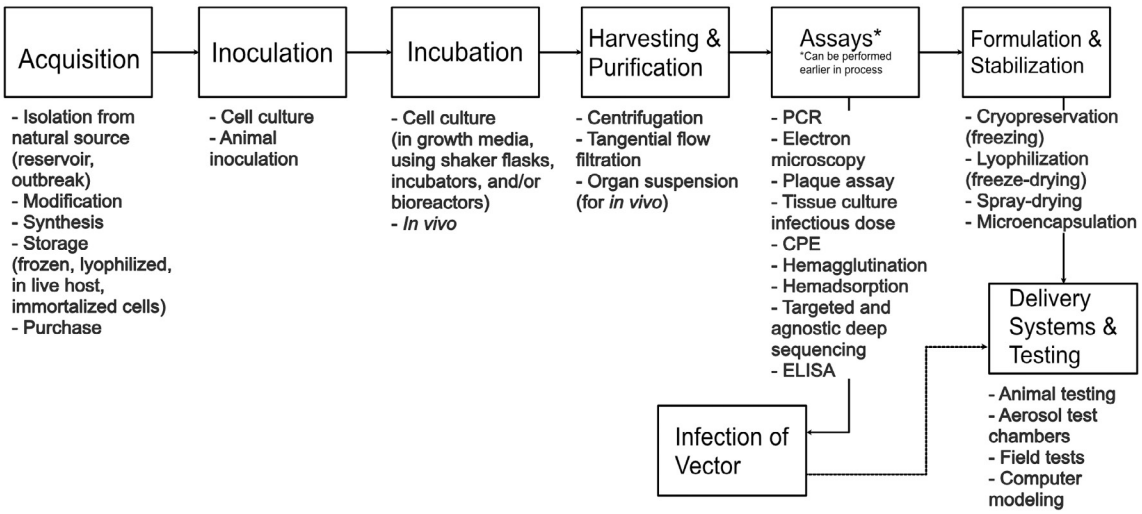
Once the scenarios were fully developed, the team used them as a basis to identify possible pathways to the acquisition of biological weapons that the hypothetical proliferator may use.

For this, the project drew on a methodology used in the nuclear non-proliferation field and developed by the International Atomic Energy Agency (IAEA), called Acquisition Path Analysis. This methodology looks at the plausible paths by which material necessary for weapons of mass destruction (in the case of nuclear weapons, weapons-usable fissile material) can be obtained, and at the processes required to do so. It maps them against the available resources of a state (in the IAEA case, their nuclear fuel cycle and other activities) to identify areas where diversion could happen and prioritizes the use of monitoring and verification resources (Nakao et al. 2015; Miller et al. 2018). While creating a general Acquisition Path Analysis for the whole biological industry is, at present, probably unfeasible, the team created dedicated acquisition paths for the scenarios. These included all the steps that would be part of the biological weapons program, from acquisition of the agent, through to weaponization, covering both technologies and organizational aspects (for a generic example, see Figure 1).[4]

3 The authors wish to highlight that all the scenarios drew from different known cases of BW production by both state and non-state actors, where appropriate, alongside hypothetical analysis of risks. No scenario is meant to represent a specific country in its past or present form.

4 Acquisition pathways – including detail on processes, techniques, equipment and materials – were drafted by the project team and validated by experts in three formal rounds of review during the project. Although the acquisition pathways drew on only open-source information, they were drafted in order to fill in an information gap in publicly available literature. Because the compilation of this information has been judged by the project team to make it more sensitive, the detailed versions of the acquisition pathways upon which the observables were based are not included in the public version of this report.

Figure 1: Example of process diagram for scenario Acquisition Pathway Analysis



Once the acquisition paths had been developed in full for each scenario, the team used them to identify "observables": these were technologies, equipment, facilities, activities, and organizational structures that would be relevant to a biological weapons capability.

Evaluating monitoring approaches

The list of observables provided a concrete reference to discuss and evaluate the potential of different monitoring approaches. The team considered various aspects of verification:

- Voluntary transparency measures, in the form of the Confidence-Building Measures (CBMs) that are already part of the BWC regime;
- Measures for formal verification – for these, the team started from the work done by VEREX in 1992–1993, and considered how the measures proposed at the time could apply to the scenarios and technologies envisioned today; and,
- Emerging and novel technologies: in this case, the team considered a number of technologies that were not available or mature during the work of VEREX, and many that are only now showing their relevance, and consider how they could be employed complementarily to other measures.

For each of these, the team compared the existing or proposed instruments to the observables and considered whether the instruments would be able to gather relevant information about the different observables. These comparisons are explained in detail in chapters 4, 5, and 6.

Validation and expert feedback

The project team sought frequent expert feedback to critique and refine the project's material throughout the process. After each of the major stages described above – the development of hypothetical scenarios, the production of acquisition pathways and observables list, and the evaluation of different monitoring approaches – the team convened a workshop to present interim results and receive feedback from high-level experts in the fields of biodefence, biological weapons non-proliferation, and related areas. Additional experts provided feedback in written form.

Learning from other regimes

The methodology sought to apply the general principles of the Acquisition Path Analysis which the IAEA has now used for over two decades in its nuclear material safeguards but framed around biological non-proliferation. It is important to note that a full replication of the Acquisition Path Analysis methodology

would go well beyond the scope of this study – and ultimately may be impossible to replicate in the biological field, due to the differences between the industries and technologies.

Matching the scope of IAEA's Acquisition Path mapping would entail further years of work; this report focuses on the highest level of mapping done under Acquisition Path Analysis, which is the state-level acquisition path. It also covers some of the more detailed levels of mapping, which break down single steps of the weapons acquisition process into different processes and technology options. The full IAEA approach goes into even greater detail, including mapping processes at the level of individual facilities, and includes assessment of the strengths of observables (Liu and Morsy, n.d.).

In addition, there are significant differences between the nuclear and biological fields that need to be accounted for. A key difference is the role and constraints of material in the weapons production process: pathogens of concern for possible biological weapons development are much more numerous than the relatively small set of materials that could be used to develop nuclear weapons. Moreover, biological agents replicate and can be cultivated, meaning that the acquisition of sufficient "raw material" at the front end of the process is not as crucial as it is in the nuclear field. This shifts the emphasis of the analysis away from the "front end" of the acquisition process, and further towards the capabilities needed for mass production and weaponization. It also leads to a more diverse, broader set of pathways that would need to be updated as biotechnology continues to progress at a rapid pace.

Despite these differences, applying the general logic of Acquisition Path Analysis to possible biological proliferation scenarios yielded useful insights into patterns of observables.

One of the advantages of this approach was that it enabled the identification of useful observables where activities for offensive purposes diverge from peaceful and prophylactic uses. This flips the usual "dual-use" problem; rather than considering it as a barrier to effective verification, it can be used to focus on the most significant areas of distinction between permitted and prohibited activities.

Moreover, using this approach to mapping observables offered a structure within which to interrogate how scientific progress impacts the threshold for acquisition, and how the specificity and strength of observables might evolve. The observables are not a static list, nor should they be treated as such. They emerged directly from the scenarios which, if a version of this methodology is adopted by States Parties, should change over time as consensus changes about which scenarios are most relevant. Within the scenarios as well, the detailed pathways of biological weapon acquisition should be updated with plenty of technical input to ensure that assumptions – about what capabilities are necessary and what one could expect to observe in association with certain activities – remain realistic and up to date.

Furthermore, the observables contain not just materials and technology, but also behaviors such as good (or bad) faith engagement with the BWC and broader disarmament regimes. This reflects calls from various experts for behavioral arms control, most recently specifically for the BWC from Kelle and Dando (2025).[5] Our approach addresses both behavioral and material aspects for compliance monitoring. It treats verification as a spectrum that includes not just detection of capabilities but also the responsible engagement by parties with compliance monitoring itself as a trust-building activity that helps to strengthen norms against biological weapons and improve the chances of cooperation amongst States Parties to resolve concerns.

Another key reason Acquisition Path Analysis proved to be a useful instrument is that it was specifically designed by the IAEA to help set priorities for verification. In the context of this project, the analysis of observables built on this methodology was used to discuss and re-evaluate the possible advantages and uses of a range of monitoring and verification measures that have been proposed in the BWC context over the years.

5 See also Kuhn, U. & Williams, H. (2023).

A cautionary note on observables

This report provides a list of observables, detailing facilities, equipment, activities and organizational approaches that could be used as part of a bioweapons program. The authors want to clarify that this list should not be seen as a "checklist", and the presence of any – or several – of these observables should not be read as non-compliance with the BWC. While the observables are related to capabilities that are necessary for the production of biological weapons, many of the same capabilities have entirely legitimate civilian applications. Simply counting the number of observables is not a reliable way to monitor or verify BWC compliance – and indeed could lead to false accusations and erode trust among state parties.

As explained above, the methodology used in this report – and the Acquisition Path Analysis used by the IAEA that informs it – looks at equipment and activities not just in isolation, but in context: how equipment is used, who carries out and funds certain activities, where sensitive material is acquired from, and where it goes after it is processed.

The observables are objects of interest for monitoring and verification not because they are inherently suspicious or dangerous, but because they offer useful reference points to understand a country's activities. Monitoring observables can help confirm that all activities are being put to peaceful use, or it may highlight ambiguities or anomalies for clarification. Experience in other sectors shows that very often ambiguities or anomalies simply reflect minor differences in how a state conducts its research or organizes its industry, rather than signs of proscribed activity.

Moreover, looking at the observables together, and the way they effectively support one another as a possible "supply chain", can help identify key nodes where, for example, material would be diverted to weapons use. In this way, a system-level outlook at the activities in a state can help prioritize verification and monitoring activities where it matters – maintaining efficacy while reducing the waste of resources.

References

Kelle, A. & Dando, M. R. (2025) Behavioral arms control in the century of biology. *The Nonproliferation Review*. [Online] 1–21. [online]. Available from: /doi/pdf/10.1080/10736700.2025.2505828?download=true (Accessed 6 October 2025).

Kuhn, U. & Williams, H. (2023) A New Approach to Arms Control. Foreign Affairs [online]. Available from: https://www.foreignaffairs.com/united-states/new-approach-arms-control (Accessed 6 October 2025).

McLeish, C. & Moon, J. R. (2020) Sitting on the boundary: the role of reports in investigations into alleged biological-weapons use. *The Nonproliferation Review*. [Online] 27 (4–6), 525–540. [online]. Available from: https://www.tandfonline.com/doi/abs/10.1080/10736700.2020.1872968 (Accessed 6 October 2025).

Miller, K. et al. (2018) *Capabilities of the Acquisition Path Analysis Tool (APAT) for Integration of Multisource Data*. p.105–105. [online]. Available from: https://inis.iaea.org/records/51m7j-vyf39 (Accessed 6 October 2025).

Nakao, A. et al. (2015) *Acquisition Path Analysis as a Collaborative Activity*. p.209–209. [online]. Available from: https://inis.iaea.org/records/x3jos-psm72 (Accessed 6 October 2025).

Ralf Trapp (2023) Chemical and microbiological forensics in investigations of alleged uses of chemical and biological weapons – a preliminary analysis, CBWNet Working Paper No. 4. https://cbwnet.org/media/pages/publications/working-paper/chemical-and-microbiological-forensics/ea2a53e0f3-1676557423/2023-0216_wp-4_trapp-forensics_web.pdf

Chapter 2

Scenarios of Biological Weapon Acquisition

As noted above, the potential scale and scope of offensive biological weapons programs is large. At one end of the spectrum a lone actor could produce and use a simple toxin (e.g., ricin) to target an individual or number of individuals. At the other end of the spectrum a perpetrator could develop, produce and use a genetically modified organism at scale on population centers or military targets. The variations within the spectrum are significant. This project used hypothetical scenarios to constrain these possibilities and focus the analysis.

The following scenarios present hypothetical countries with different types of biological weapons programs, outlining the core goals and resources of the programs and the different pathways to acquisition and production. The scenarios are informed by historical cases, academic research, and prospective considerations of emerging technologies. They were further iterated and refined through input of U.S. Department of State experts and experts in the governmental and non-governmental field, who provided feedback in written form and during a workshop held in Geneva in December 2023.

Scenario A

This scenario describes a large program using fairly conventional technologies, dispersed at multiple sites. This is consistent with older historically known biological weapons programs.

Stage 1: General Scope and Goals

- This scenario features a state perpetrator whose goal is to use biological weapons against another state or a large non-state group (such as an ethnic minority).
- Targets include a human subpopulation (large groups) or the food supply (crops).
- The perpetrator's rationale for use of biological weapons rather than conventional weapons include:
  - Strategic use (deadly agents employed as a last resort/deterrent);
  - Operational use (reaching deep military targets and incapacitating battlefield leadership)
  - Arms races (whether actual or perceived);
  - Impact on an adversarial state's economy and healthcare system;
  - Political suppression of a sub-population; and/or
  - Deniability.
- The program is large-scale and dispersed across multiple sites.
- Biological agents are selected for desired qualities based on the rationale for biological weapons use. In cases of strategic use, agents would be highly transmissible and associated with high mortality in presence of limited or total absence of medical countermeasures (MCMs). Agents that can be stabilized and dispersed relatively easily would be a focus.
- Agents would be acquired through isolation from a natural source, repositories, or provision from another state.

Stage 2: Infrastructure and Technology

- Once a program is well-established, production infrastructure would be at manufacturing scale.
- A scenario considering this type of program at a nascent stage may have pilot scale facilities or convert civilian manufacturing facilities as needed.
- Stockpiling, storage, and large-scale manufacturing would be energy-intensive with high resource consumption to maintain operations.
- During early phases of a program, sophistication could range but a well-established program has fully developed organizational roles, knowledge retention, training structures, and moderate to high reliability of processes with quality assurance methods.
- This program uses conventional and well-established technologies that have been used in past programs.
- Steps for upstream processing involve inoculation, microbial fermentation or cell culture, harvesting, and sterilization and decontamination of equipment.
- Steps for downstream processing involve extraction or separation, purification and quality checks, suspension and refrigeration/freezing (if in liquid form) or drying (if in powder form), weaponization, and sterilization and decontamination of equipment.
- Processing requires large machinery and extensive biosafety measures, including vaccination campaigns for personnel.
- Some agents would be stored in a reserve supply or munitions. This would pose a challenge, as it requires highly specialized knowledge and technology not used in research with a legitimate purpose, would have a large energy footprint for maintaining proper atmospheric conditions, and require a dedicated site. Maintenance of a laboratory culture is also a likely necessity.
- The most likely delivery method is aerosolization, though the scenario also considers contamination of water/food sources or release of infected vectors.
- Training, testing and deployment includes field testing or in silico prediction models, integration in military doctrine, vaccinations and vaccine/MCM development, and other indicators associated with past offensive programs.

Stage 3: Adding Details to the Scenario, Creating an Overview of Resources Available to the Fictional Biological Weapons Program

- Equipment would be either available in-country from dual-use pharmaceutical, vaccine, or food facilities, or could be acquired from another state.
- Military facilities are most likely to provide the equipment for munitions.
- Facilities include clandestine facilities dedicated to biological weapons production, and the capability to repurpose dual-use facilities to produce biological weapons on short notice.
- Compartmentalization of personnel is likely, with subcontractors and/or large numbers of regular employees unaware of the overarching purpose of their work at various stages. An assumption is that Country A would hide some things but not all, and the role of whistleblowers must be considered. Some large industry partners would do most of their own work, specialization and not outsourcing, but this would have risks and bottlenecks.
- Funding comes from a combination of military funds and government funds for research institutions. Such a program would not exist in isolation, so some cross-governmental awareness would be necessary (e.g., material acquisition, funding, personnel, and training).
- The country has knowledge/personnel from research institutions working in microbiology (for agent selection and acquisition, design of BW, and R&D involved in process design and testing of the biological weapons including computational biologists), pharmaceutical and biotechnology industry

(for scaling up production, maintenance and design of equipment, and process support and operations), and munitions expertise from the military (who are also likely to store stockpiles and keep inventory).

- Military research institutes are involved with the full process, from R&D to weaponization.

Scenario B.1

This scenario describes a small and highly sophisticated program at the early stages of development, mostly dealing with the R&D aspects; this would have a focus on novel and emerging tech and experimental activities, and would help us focus subsequent analysis on how to spot any red flags from those early activities.

Stage 1: General Scope and Goals

- This scenario features a state perpetrator aiming to develop potentially highly asymmetric biological weapons that circumvent established detection methods, response plans, and treatment regimens.
- Targets include human subpopulations from individuals (e.g., assassinations) to large groups.
- The perpetrator's rationale for development of novel biological weapons could include:
  - Arms racing (actual or perceived);
  - Effectiveness against guerilla warfare;
  - Deniability;
  - Compounding effects such as undermining adversarial states through disinformation campaigns;
  - Exploiting lack of pandemic preparedness and overwhelming their healthcare systems, or causing economic damage; and
  - Signaling capacity and willingness to violate norms and intimidation (psychological impact).
- The program is small-scale, and unlikely to include any stockpiled agent or munitions.
- Biological agents are selected or modified for their ability to circumvent existing detection techniques and MCMs. They may also be intentionally dual-use strains common in peaceful research that are similar to high-priority agents (i.e., vaccinia virus as a surrogate to the closely related variola virus). They may be tailor-made for their intended use.
- Acquisition and/or development of agents involves the following:
  - Viral vectors to target victims' genomes (either germ-cell [reproductive] or somatic) and induce disease (gene therapy as a weapon);
  - De novo synthesis of a virus (e.g., using sequence information to generate variola virus "from scratch");
  - Use of artificial intelligence (AI) for agent selection and/or modification;
  - Use of CRISPR or other approaches for genetic engineering (e.g., augmenting infectivity, pathogenicity, virulence, resistance to MCMs, stability);
  - Creation of chimera agents or modification of zoonotic agents to infect specific subpopulations;
  - Bioregulators and peptides (that could be easily hidden in plain sight, as much of this research is done for legitimate medical reasons).

Stage 2: Infrastructure and Technology

- The scenario assumes that production infrastructure remains at laboratory scale (and maybe pilot scale).
- This is a relatively new program in an exploratory R&D phase.
- There is a small group of personnel working on this alongside civilian research or defensive biological weapons research. The effort is spread across a few laboratories. Training and knowledge retention

may be unstructured, with informal organizational roles for the biological weapons program (instead relying on pre-established roles in labs or highly compartmentalized knowledge/research). This could also be a legitimate program but with some infiltration by people who siphon interesting research results and channel them to offensive activity or further research elsewhere.

- Research is actively in progress, with either dual-use research outputs or delays in research outputs for peaceful purposes.
- The program employs emerging technologies.
- Agents are not yet stored in a large reserve supply, and a scaled-up process for biological weapons production is not yet in place. Batch production and maintenance of a laboratory culture are assumed.
- There may be inoculation and microbial fermentation/cell culture on a laboratory/pilot scale. Work would take place in laboratories akin to US biosafety levels BSL-3, BSL-3+ or BSL-4.
- Downstream processing is less likely. If present, it would include R&D efforts and research into the shelf life of agent and weaponization feasibility studies.
- Delivery methods are in the R&D phase only. They may include work on aerosolization, transdermal (micro-patches, small punctures [e.g., toxin-covered pellets]), transmission via vectors and contamination (e.g., absorption by contact, stability in certain conditions).

Stage 3: Adding Details to the Scenario, Creating an Overview of Resources Available to the Fictional Biological Weapons Program

- Diversion of equipment and capital normally used in civilian research institutes and military defense research.
- This program entails the smallest outlay of capital and lowest chance of detection if Country B were to set up a clandestine, dedicated laboratory space for this research.
- There would be an indigenous research capacity, with established expertise in microbiology or virology. There would also be extensive AI capabilities, expertise in genetic engineering, vaccine process design, epidemiology, and access to big biological datasets (e.g., results of ancestry testing) in-country.
- Personnel would be pulled from a military research laboratory or a private laboratory that has previously worked closely with or receives considerable funding from the government. One interesting dynamic to note is that this program would require high investment for a relatively small military advantage and/or potentially small returns and may be opposed by government/military leadership.

Scenario B.2

This scenario describes a small and sophisticated program, fundamentally similar to the one covered by Scenario B.1 above but seen at a later stage of development. This scenario focuses on scaling-up production, manufacturing (possibly including delivery systems) and training of personnel. This program would show signs of maturity, including knowledge management, procurement of production technology for higher volume than that of B.1, and logistics activities (such as on-demand production or small-scale stockpiling).

Stage 1: General scope and goals

- This scenario features a state perpetrator aiming to operationalize research into dual-use emerging technologies to create highly sophisticated biological weapons.
- The perpetrator's rationale and targets remain the same as in Scenario B.1. Unlike in Scenario A, there is no focus on battlefield use.
- The program is small to medium in scale (smaller than Scenario A but larger than Scenario B.1). It may be stockpiling agent or focusing on on-demand production.

- Biological agents are selected or modified for their ability to circumvent existing MCMs. They include intentionally dual-use agents common in peaceful research that are similar to high-priority agents.

Stage 2: Infrastructure and Technology

- Production infrastructure is likely to be at pilot scale or small manufacturing scale.
- The program is more mature than Scenario B.1, with structured processes for recruitment, training and knowledge retention. The organizational roles are well defined and responsibilities mostly consistent.
- There is continuous quality control and testing of agents and dispersal methods (a "menu") to achieve reliable results.
- Testing would be as limited as possible; if there is open-air or aerobiology laboratory testing, safety issues would emerge. Animal caging and other infrastructure, and waste management for live animal testing would be evident.
- This program uses both conventional technologies and emerging technologies.
- Processes may be batch or semi-continuous. There may be a goal to establish and maintain stockpiles, but designed processes are likely to be set up for reliable just-in-time production. We assume maintenance of lab cultures in either case.
- There is a sophisticated capacity for both upstream (inoculation, microbial fermentation/cell culture, harvesting) and downstream (extraction/separation, purification, analysis, suspension if in liquid form/stabilization as a powder) processing, possibly with single-use tubing and lining for equipment.
- Agents could be integrated with conventional delivery systems (such as aerosols in munitions) or there could be R&D of sophisticated delivery systems, such as:
    - Drones (uncrewed aerial vehicles);
    - Food sources;
    - Two-stage vectors with mold, bacterium, viral or insect delivery of a genetic modification aspect in a target population; and/or
    - Fomites.
- Munitions are hard to develop and hide. Typically, munitions would include a liquid that upon deployment and use produces aerosols. Aerosol vaccine research could be used as a cover in some cases.

Stage 3: Adding Details to the Scenario, Creating an Overview of Resources Available to the Fictional Biological Weapons Program

- Equipment could be diverted from legitimate vaccine industry or commissioned in-country for a fully clandestine facility.
- Government funding would be necessary, even if the effort were highly compartmentalized, and the program would likely be hidden deep within military and/or intelligence structures. Some kind of coordination center would be needed.
- Personnel involved in the program would not have knowledge of real-world impacts, direct contribution to the program, or distribution among laboratories and facilities. The program would use acculturation to shift values and beliefs and incentivize personnel with perks and privileges.
- If very small scale with limited personnel, there may be corruption, self-aggrandizement, and internal politics that create challenges for the program.
- It is likely that some personnel will have experience with computational modelling, including AI.
- Some personnel would disappear into the programs or engage differently with the wider scientific community (i.e., different pattern of publications, appearance at conferences). The most promising students who return from study exchanges may be recruited into the program and hidden.

- The number of states/countries that could harbor this program is likely to be small. Thus, traditional barriers (e.g., export control lists) may not be relevant.

Scenario C

This scenario describes a small and highly secretive program using fairly common technologies that are more readily accessible than the ones described in Scenarios B.1 and B.2.

Stage 1: General Scope and Goals

- This scenario features a state perpetrator whose goal is to use biologically derived toxin weapons against another state or internally against individual political dissidents.
- The perpetrator's rationale for use of biological rather than conventional weapons centers on:
  - Plausible deniability; and
  - The psychological terror associated with toxin weapons.
- The program is small-scale and may be contained at a single site.
- Agents would be selected based on their effectiveness and known properties as a biologically derived toxin weapon; novel agents are unlikely.
- Agents would be acquired through isolation from a natural source.

Stage 2: Infrastructure and Technology

- Production infrastructure would be at pilot scale once the program is well-established. A nascent program may have laboratory scale facilities.
- The organizational structure includes a small group of personnel that are entirely compartmentalized, with only a few senior members communicating with outside bodies. Training and knowledge retention may potentially be unstructured due to the small size of the program.
- This program uses conventional and well-established technologies that have been used in past programs.
- Steps for upstream processing could involve microbial fermentation, harvesting, and sterilization and decontamination of equipment.
- Steps for downstream processing would involve extraction or separation, purification, suspension and refrigeration/freezing (if in liquid form) or drying (if in powder form), weaponization, and sterilization and decontamination of equipment.
- Just-in-time production is most likely, though some agent could be stored in stockpile or munitions. Maintenance of a laboratory culture is possible.
- Batch production is assumed, with an emphasis on just-in-time process design.
- The most likely delivery methods are transdermal (e.g., pellets, microneedles), or contamination of water/food sources and high-touch surfaces. Aerosolization may also be explored.

Stage 3: Adding Details to the Scenario, Creating an Overview of Resources Available to the Fictional Biological Weapons Program

- Equipment would be either available in-country from dual-use pharmaceutical, vaccine, or food facilities, or could be acquired from another state.
- Facilities would be clandestine and dedicated to biological weapons production; however, the equipment would be dual-use and easily disguised to appear dedicated to peaceful or prophylactic purposes.

- Funding may come from either military funding or government funding for research institutions, though it is unlikely that more than one government body would oversee the program. The program may be disguised as civilian industry.
- The program would have personnel from research institutions working in microbiology and toxicology (for agent selection and acquisition), pharmaceutical or food-processing industry (for scaling up production, maintenance and design of equipment, and process support and operations), and the military (for weaponization and delivery). These personnel may cease publications and networking activities upon their entry into the program.
- Legitimate military research institutes are distanced from the clandestine program.

Chapter 3

Observables

It stands to reason that monitoring requires observation; designing a monitoring regime entails having an idea of both what its subjects are (i.e. what to monitor), and what further actions should be taken (i.e. further monitoring, consultation, etc.) on the basis of what is observed. Thus, this project's methodology sought to specify observables from more abstract overarching scenarios of noncompliance with the BWC. This chapter details the observable signs of the scenarios developed in the previous chapter.

These were identified by reviewing the fully developed pathways and carefully identifying what could be seen, heard, read, or otherwise observed about them. Essentially, this entailed asking: What about [step in acquisition pathway] could be externally visible to the most intrusive monitoring conceivable? This process was of course somewhat subjective, given that some level of discernment was necessary to avoid listing observables so mundane as to be completely irrelevant for monitoring. Further, the proliferation pathways for biological weapons are far more varied and flexible than for nuclear weapons. Just as the scenarios are a subset of a much broader realm of noncompliance, the observables are a subset of the various potential proliferation pathways for each scenario.

Following are key divergences between the patterns to be expected with activities for peaceful and prophylactic purposes and those undertaken for offensive purposes. The detailed lists of observables follow in Tables 1–4. It bears noting that whereas emphasis was placed on the divergence of biological weapons development from peaceful biology, most of the observables in the detailed tables below are simply a reflection of capacity and could equally be present in peaceful and prophylactic contexts.

Scenario A

- Observables that indicate large-scale manufacturing:
  - High level of containment in processing, inconsistent with typical manufacturing practice
  - Purchase of reagents (growth media, serums, buffers, antibiotics, etc.)
    - That are not in line with standard manufacturing practices for the purported product(s)
    - In large quantities without a clear end use
    - Through a rotation of multiple suppliers (which could be done to disguise true quantities purchased)
  - Missing or conflicting records of operations (which could indicate batch test runs of biological weapons production in dual-use facilities)
  - Mothballed but still-working equipment in pharmaceutical facilities (which could indicate a latent production line)
  - Biosafety measures not typical for facilities ostensibly meant for civilian use
    - Stringent containment during downstream processing (in contrast to vaccine production, which usually uses high containment only before attenuation)
    - Overly thorough treatment of waste streams

        - Use of disposable plastic jackets and piping for fermentation vessels in a context not normally used
    - General security measures not typical for civilian facilities
- Observables of research being conducted for offensive purposes:
    - Unusual levels of integration between various defensive research projects, particularly upstream and downstream
        - E.g., The same funding stream is directed both towards a laboratory working on gain-of-function experiments including influenza A virus and a laboratory modelling aerosol dissemination of viral particles
        - E.g., Scientists and facilities overlapping between animal testing and formulation and stabilization steps (which could indicate optimization of formulation for delivery)
        - Work with animal models in experimental programs
        - Aerosolization facilities in static or dynamic test chambers
- Signs of collection of dangerous strains of bacteria, either through field research or repositories, without corresponding research into mcms
- Unusual outbreaks, deaths of relevant scientists, or strict culture of repressing information and accountability on biosafety accidents
- High levels of secrecy in general and stringent clearance requirements
- Any reports of a clandestine field-testing location or import of high numbers of nonhuman primates
    - Large pens
    - Mass animal culling and cremation/burial
- Military storage sites with large-scale refrigeration
- Changes in military vaccination and MCMs (including seemingly innocuous vaccine development)
- General lack of transparency when asked about dual-use activities and capabilities

Scenario B

The main issue with scenario B would be the extensive dual-use capability, and its ability to hide its latent sophisticated research and production for offensive purposes behind uses of the same scientific expertise and equipment that it leverages consistently for peaceful and prophylactic purposes. It is likely that some of the personnel involved in an offensive program would not even be aware of the fact, as the most significant deviations from peaceful development would take place in the laboratory, before scale-up, and at the very end, in preparation of delivery systems and strategies for weaponization. Sandwiched among these small covert efforts could be several civilian organizations (private industry, academic institutions, etc.) that have little to no awareness of their culpability. As activities become more unambiguously offensive (such as, weaponization research and practice with scale-up of agents, rather than analogues), they would be hidden within a military program.

However, there are a limited number of countries with the resources necessary to conduct a program of this level of sophistication and hide it behind their normal activities. Thus, monitoring dual-use research outputs may be the single most useful activity to detect observables; but this work-intensive monitoring need not be applied globally, only to countries with well-developed biotechnology and life sciences industries and their closest allies.

- R&D of mRNA vaccines is more favorable than that of DNA due to their easier delivery, lower costs, and safety (as they cannot affect the target individual's genetic code). DNA vaccines are more thermally

stable (meaning easier to store) and integrate into the genome but usually require an electric impulse for uptake into cells.

- If private manufacturing facilities are used for scale-up of viral agents, then some infection amongst personnel who are unaware of the risks posed by the live viruses they are handling may be expected.
- Military-run vaccine production facilities, or a private vaccine manufacturer which fails to confirm the sequence, purity, and virulence of any seed virus provided to it. The absence of records of these studies could be an indicator (along with the absence/inconsistency of downstream testing results against assays provided by the laboratory).
- High levels of secrecy, or reports of lax screening protocols by an in-country commercial synthesizer.
- Specific types of vaccination that, as in the case of influenza A virus, differ from the dominant annual vaccine based on expected strain.
- Microbial forensics: once a genetically modified influenza A virus has been released, there may be some "signatures" indicating a specific laboratory or country has developed a strain, either based on its similarity to endemic strains or known libraries, or on the basis of the techniques used to edit the virus's genome.

Scenario C

Though the opportunities to disguise facilities and equipment as dual-use and intended for civilian uses may be more limited for this program, there are specific industries that may provide cover, even if Country C does not possess an extensive pharmaceutical industry. Food and beverage industries could provide equipment which could be retrofitted for biological weapons production. Further, a domestic castor oil production capability is almost a prerequisite if Country C wants to produce ricin in any significant amount. Apart from the agent itself and the level of containment necessary for the production process, it would be very hard to distinguish between B. anthracis and B. thuringiensis biopesticide production. A biopesticide plant would use a similar process flow, equipment, materials, expertise, storage, and dispersal, as the biopesticide is formulated for spraying crops.

- Are there legitimate uses for lyophilizers or spray-dryers in Country C? If so, is the amount imported inconsistent with production needs or missing end-user certification?
- Is there justification for BSL-3/4-like equipment, maybe without transparency about facilities? If there is diversion of some equipment to the program, this would require a slightly broader circle of people in the know.
- Have there been medical imports of non-vaccine strains of *B. anthracis*, microneedles, and anthrax or ricin vaccines (the latter of which would be especially telling, as ricin vaccines are still in clinical trials and not widely available)?
- Have there been any cases of ricin poisoning? Have there been any outbreaks of anthrax among domestic animals?
- Have there been any detected processing activities with castor oil byproduct past the cold-pressing stage?
- Have any scientists studied biopesticide production and since disappeared regarding employment and publications?

Consolidated Observables Lists

Table 1: Common observable signs of potential offensive capabilities across the three scenarios

	Observables
R&D	Unusual levels of integration between defensive research projects
	Same funding stream directed to labs working on gain-of-function experiments and aerosol dissemination modelling
	Scientists and facilities overlapping in animal testing, formulation, and stabilization steps
	Work with animal models and nonhuman primates in experimental programs
	Aerosolization in static or dynamic test chambers
	Unusual outbreaks
	Deaths at relevant facilities (of relevant scientists)
	Biosafety accident reporting
	Reports of clandestine field-testing locations or large imports of nonhuman primates
	Ex-bioweaponeers moving to foreign labs
	Refrigeration at military storage sites
	Lack of transparency when asked about dual-use activities and capabilities
	Linkages between pharma company and military complex
	Animal testing which cannot be corroborated by published literature
Diplomatic Engagement	Abuse/bad faith engagement with arms control and non-proliferation forums (BWC, UNSGM, WHO, WOAH, FAO, UNSCR)
	Disinformation, delaying tactics or disruption of substantive decisions in arms control and non-proliferation forums
	Vetoing UNSC resolutions
	Lack of transparency during consultations
	Accusations of other states possessing a bioweapons program
Public Sentiment & Internal Shifts	Shifts in public opinion on biological and chemical weapons
	Buzz on social media and in news media about specific facilities

Table 2: Observable signs of potential offensive capabilities in Scenario A

	Observables
Dual-use divergences in large-scale manufacturing	Non-attenuation of viruses/non-modification or gene drives of bacteria to select for prime antibiotic traits
	Purchase of reagents (growth media, serums, buffers, etc.) not in line with standard manufacturing practices
	Missing or conflicting records of operations
	Mothballed but still-working equipment in pharmaceutical facilities
	Overly thorough treatment of waste streams
	Use of disposable plastic jackets and piping for fermentation vessels
	Stringent containment during downstream processing
Equipment & Facilities	Construction of high/maximum containment facilities
	Clarity of organizational structure at high/maximum containment facilities
	High/maximum containment facilities funded by military budget
	High/maximum containment facilities built by a private company
	Remote locations of high/maximum containment facilities
	Abnormally high security at high/maximum containment facilities
	Bio-pesticide production facility with high-level containment measures
	Very high energy usage (freezers) at high/maximum containment facilities
	Import/manufacture of equipment on AG control list
	Crop sprayers
	Process control software and instrumentation
	Cryogenic freezers (under -80C)
Materials	Pathogenic agents (*Yersinia pestis, Francisella tularensis, Vibrio cholerae, Clostridium botulinum*)
	Known strains in country possession
	Materials/agents purchased from commercial providers if used in legitimate research
	Materials/agents illicitly acquired through unofficial networks
	Research on high-risk pathogenic agents in areas where these pathogens are endemic
	Additives for encapsulation of probiotics
	Animal models (primate or small mammal)
Expertise & Human Resources	Academic research on high-risk pathogenic agents (including sudden cessation of publications)
	Lack of public job postings for relevant sites
	Expertise on dispersion modelling, simulation, toxicology, drug delivery, etc.
Defense & Military	Small elite military squadrons linked to R&D or intelligence services
	Changes to budget allocations for R&D/CBRN
	Government tender sites calling for pharmaceutical industry support
	Changes to frequency and scope of CBRN exercises
	Mass military vaccination campaigns
	Prophylactic stockpiling (e.g., antibiotics)

Table 3: Observable signs of potential offensive capabilities in Scenario B

	Observables
Dual-use divergences	Extensive dual-use R&D capability (with potential for concealment of offensive activities)
	Extensive later stage dual-use capability (with potential for concealment of offensive activities)
	Personnel unaware of offensive nature of their work
	Civilian organizations (sub-contractors) unknowingly involved in offensive activities
	Use of private vaccine manufacturers of viral agents
	Infections amongst private manufacturing personnel unaware of risks
	Absence of testing record to confirm receipt of correct candidate vaccine
	Inconsistencies in downstream testing results
R&D	Weaponization (clear intent) research and scale-up of agents
	Signature identification through microbial forensics
	Specific vaccination campaigns differing from standard vaccine strains
Equipment & Facilities	Construction of high/maximum containment facilities
	Construction of small and dual-use facilities
	Clarity of organizational structure at high/maximum containment facilities
	High/maximum containment facilities funded by military budget
	Equipment procurement outsourced to contractors
	Import/manufacture of equipment on AG control list, e.g. peptide synthesis machines
	Biological simulation platforms (machine learning, cloud labs)
	Large freezers to store viruses and genetic material
	Single-use plastic incubators, shaker flasks, small bioreactors
	PCR/qPCR
Materials	Pathogenic agents (Influenza virus, mammalian or avian)
	Mammalian cell culture or fertilized chicken eggs
	Materials for genetic editing & synthesis
	Materials for mRNA vaccine production
	Microparticles/nanospheres for delivery
	Animal models (primate or small mammal)
Expertise & Human Resources	Academic research on high-risk pathogenic agents (including sudden cessation of publications)
	Expertise on vaccine process engineering, virology, toxicology, molecular biology, epidemiology, immunology
	Delayed or less frequent publications
Defense & Military	Small elite military squadrons linked to R&D or intelligence services
	Changes to budget allocations for R&D/CBRN
	Changes to frequency and scope of CBRN exercises
	Mass military vaccination campaigns

Table 4: Observable signs of potential offensive capabilities in Scenario C

	Observables
Dual-use divergences	Unusual production patterns of food and beverage industries
	Choice of spore producing biopesticides (e.g., B. thuringiensis)
R&D	Use of B. anthracis and ricin in R&D activities
	Medical imports of non-vaccine strains of B. anthracis
	Scientists studying biopesticides who later disappear
Equipment & Facilities	Construction of high/maximum containment facilities
	High/maximum containment facilities funded by military budget
	Clarity of organizational structure at high/maximum containment facilities
	Remote locations of high/maximum containment facilities
	Abnormally high security at high/maximum containment facilities
	Import/manufacture of equipment on AG control list
	Castor oil production with cold pressing
	Pharmaceutical grade milling machine
	Integrated containment systems in equipment or operation under high-containment protocols
	Full-body PPE
	Sprayer tanks
	155-mm shells
	Microneedles
	Centrifuge with in-situ sterilization
	Uncrewed aerial vehicles for dispersal
	Flow filtration
Materials	Pathogenic agents
	Growth of castor beans
	Ammonium sulfate
	Research on B. anthracis when endemic in the country's soil
	Use of solvents that enhance dermal absorption
	Kinases
	Small mammals for field-testing
Expertise & Human Resources	Academic research on high-risk pathogenic agents (including sudden cessation of publications)
	Inoculation of wild-type bacterial strains from samples
	Fermentation knowledge from the dairy/beverage industry
	Expertise on toxicology
Defense & Military	Small elite military squadrons linked to R&D or intelligence services
	Emphasis on UAVs
	Prophylactic stockpiling
	Denial of access to certain open areas (possible field testing)

Chapter 4

Confidence-Building Measures for Compliance Monitoring

This chapter looks at the BWC CBMs and considers whether they are able to capture the observables identified by the project team. The CBMs are not, per se, a form of verification; however, there are several reasons to start this analysis from the CBMs before proceeding to consider proposed verification measures. Firstly, transparency (of which the CBMs are an example) and verification are often seen to be complementary and mutually reinforcing. Secondly, the CBMs are at present the only mechanism the BWC has for capturing observable signs.

Measures to increase transparency and confidence in compliance

The confidence-building measures (CBMs) were agreed at the Second Review Conference in 1986. Anchored in article V, the CBMs were introduced as a compromise measure following renewed calls to strengthen the BWC with a legally binding verification regime. At the time, it seemed plausible that a verification mechanism was going to be put in place that resembled the declarations and on-site inspections that were being negotiated at that time for the Chemical Weapons Convention (CWC). Moreover, many BWC States Parties argued that it would be better to first conclude the negotiation of the CWC, which could then serve as a model for a possible BWC verification protocol. As such, the CBMs were adopted by consensus as an interim measure "in order to prevent or reduce the occurrence of ambiguities, doubts and suspicions, and in order to improve international co-operation in the field of peaceful bacteriological (biological) activities."

As it turned out, the verification protocol was not attainable in the 1990s or 2000s, and the CBMs remain the core, formal mechanism whereby BWC States Parties exchange compliance-related information on a regular basis.

The CBMs were elaborated at a meeting of scientific and technical experts in 1987. They were modified and considerably expanded at the Third Review Conference in 1991. The emphasis between the end of the Cold War and the Fifth Review Conference in 2001 on seeking verification resulted in decreased interest in further developing the CBM measures. The Sixth Review Conference in 2006 agreed on various improvements to their submission and distribution mechanisms, but political differences meant the CBMs remained substantively unchanged until minor modifications to the reporting forms were adopted at the Seventh Review Conference in 2011.

Although the CBMs are not derived directly from the text of the Biological Weapons Convention itself, the Second Review Conference resulted in a consensus decision that States Parties were to annually submit the six agreed forms "on the basis of mutual co-operation". That decision means participation in the CBMs is a politically binding requirement for all BWC States Parties.

Overall participation in the mechanism remains limited, but participation is steadily increasing and now stands at over fifty per cent, and key states with significant biodefense programs and sophisticated biological research communities all participate. To maximize transparency, an increasing number of States Parties are also making their CBM submissions publicly available.

This chapter considers how well the CBMs capture signs of potential offensive capabilities.

Capturing observable signs of offensive capabilities

A set of wide-ranging observable signs of potential offensive capabilities was identified through the three scenarios described in earlier chapters. Some observables are common across the three scenarios; others are scenario specific. All are listed in Tables 1–4. The tables also indicate whether the observables are captured in the CBMs.

The data demonstrates that the information requested on the current CBM forms captures a significantly small proportion of the observable signs identified of potential offensive capabilities.

More specifically, of the 21observable signs common across the three scenarios (divided into four categories: 'R&D', 'diplomatic engagement', 'public sentiment', and 'internal shifts'), the CBMs capture just over ten per cent. They partially capture another (roughly) forty per cent. Roughly half of the common observable signs of potential offensive capabilities are not captured.

In scenario A, of a large offensive program using conventional technologies dispersed at multiple sites, 35 scenario-specific observable signs were identified and the CBMs capture around thirty per cent of these. They do not capture over seventy per cent of the observables. The observables were divided into five categories: 'dual-use divergences in large-scale manufacturing', 'equipment & facilities', 'materials', 'expertise & human resources', 'defense & military'. When these are combined with the observables common across the scenarios, the CBMs capture and partially capture just under forty per cent, and do not capture over 60 per cent.

In scenario B, of a small and highly sophisticated program, 34 scenario-specific observable signs were identified and the CBMs approximately capture twenty per cent and partially capture another ten per cent of these. They do not capture more than seventy per cent of the observables. Like in scenario A, the observables were divided into categories of 'dual-use divergences', 'equipment & facilities', 'materials', 'expertise & human resources', 'defense & military', but an additional category of 'R&D' was added, bringing the total categories of observables in scenario B to six. When these are combined with the observables common across the scenarios, the CBMs capture and partially capture just under forty per cent, and do not capture over sixty per cent, as was the case in scenario A.

In scenario C, of a small clandestine program using fairly conventional technologies, 36 scenario-specific observable signs were identified and the CBMs capture twenty-five per cent of these. They do not capture seventy-five per cent of the observables. The observables were divided into the same categories as in scenario B and when these were combined with the observables common across the scenarios, the CBMs capture and partially capture thirty-five per cent of the observables and do not capture sixty-five per cent.

More granular details of the data are provided in Table 5.

Table 1: Common observable signs of potential offensive capabilities across the three scenarios

	Observables	Captured in CBMs?
R&D	Unusual levels of integration between defensive research projects	Yes
	Same funding stream directed to labs working on gain-of-function experiments and aerosol dissemination modelling	Partially
	Scientists and facilities overlapping in animal testing, formulation, and stabilization steps	Partially
	Work with animal models and nonhuman primates in experimental programs	Partially*[1]
	Aerosolization in static or dynamic test chambers	Yes
	Unusual outbreaks	Yes
	Deaths at relevant facilities (of relevant scientists)	Partially
	Biosafety accident reporting	Partially
	Reports of clandestine field-testing locations or large imports of nonhuman primates	No
	Ex-bioweaponeers moving to foreign labs	No
	Refrigeration at military storage sites	No
	Lack of transparency when asked about dual-use activities and capabilities	No
	Linkages between pharma company and military complex	Partially
	Animal testing which cannot be corroborated by published literature	Partially
Diplomatic Engagement	Abuse/bad faith engagement with arms control and non-proliferation forums (BWC, UNSGM, WHO, WOAH, FAO, UNSCR)	Partially*[2]
	Disinformation, delaying tactics or disruption of substantive decisions in arms control and non-proliferation forums	No
	Vetoing UNSC resolutions	No
	Lack of transparency during consultations	No
	Accusations of other states possessing a bioweapons program	No
Public Sentiment & Internal Shifts	Shifts in public opinion on biological and chemical weapons	No
	Buzz on social media and in news media about specific facilities	No

'Yes' is identified in cases where the CBMs have the potential to capture the observable sign

*1 CBMs can capture military experiments with animal models but not civilian.

*2 Incomplete CBMs or lack of engagement with the CBM process itself, as well as any consultation and clarification process following on from submissions, can itself be a sign of bad faith engagement with the regime. Of course, it could also be the result of resource constraints or a lack of national capacity/coordination.

Table 2: Observable signs of potential offensive capabilities in Scenario A

	Observables	Captured in CBMs?
Dual-use divergences in large-scale manufacturing	Non-attenuation of viruses/non-modification or gene drives of bacteria to select for prime antibiotic traits	No
	Purchase of reagents (growth media, serums, buffers, etc.) not in line with standard manufacturing practices	No
	Missing or conflicting records of operations	No
	Mothballed but still-working equipment in pharmaceutical facilities	No
	Overly thorough treatment of waste streams	No
	Use of disposable plastic jackets and piping for fermentation vessels	No
	Stringent containment during downstream processing	No
Equipment & Facilities	Construction of high/maximum containment facilities	No
	Clarity of organizational structure at high/maximum containment facilities	Yes*[1]
	High/maximum containment facilities funded by military budget	Yes*[1]
	High/maximum containment facilities built by a private company	Yes*[1]
	Remote locations of high/maximum containment facilities	Yes*[1]
	Abnormally high security at high/maximum containment facilities	No
	Bio-pesticide production facility with high-level containment measures	Yes
	Very high energy usage (freezers) at high/maximum containment facilities	No
	Import/manufacture of equipment on AG control list	No
	Crop sprayers	No
	Process control software and instrumentation	No
	Cryogenic freezers (under -80C)	No
Materials	Pathogenic agents (*Yersinia pestis, Francisella tularensis, Vibrio cholerae, Clostridium botulinum*)	Yes*[1]
	Known strains in country possession	No
	Materials/agents purchased from commercial providers if used in legitimate research	No
	Materials/agents illicitly acquired through unofficial networks	No
	Research on high-risk pathogenic agents in areas where these pathogens are endemic	Yes
	Additives for encapsulation of probiotics	No
	Animal models (primate or small mammal)	No
Expertise & Human Resources	Academic research on high-risk pathogenic agents (including sudden cessation of publications)	Yes*[2]
	Lack of public job postings for relevant sites	No
	Expertise on dispersion modelling, simulation, toxicology, drug delivery, etc.	Yes*[1]
Defense & Military	Small elite military squadrons linked to R&D or intelligence services	No
	Changes to budget allocations for R&D/CBRN	Yes
	Government tender sites calling for pharmaceutical industry support	No
	Changes to frequency and scope of CBRN exercises	No
	Mass military vaccination campaigns	No
	Prophylactic stockpiling (e.g., antibiotics)	No

'Yes' is identified in cases where the CBMs have the potential to capture the observable sign

*[1] Only P4/BL4 or biodefense relevant pathogens/facilities/staff are captured in CBMs

*[2] CBMs capture the publication policy for national biological defense research programs, but the scope is limited and does not involve publication surveillance.

Table 3: Observable signs of potential offensive capabilities in Scenario B

	Observables	Captured in CBMs?
Dual-use divergences	Extensive dual-use R&D capability (with potential for concealment of offensive activities)	No
	Extensive later stage dual-use capability (with potential for concealment of offensive activities)	Yes
	Personnel unaware of offensive nature of their work	No
	Civilian organizations (sub-contractors) unknowingly involved in offensive activities	Partially
	Use of private vaccine manufacturers of viral agents	Partially*1
	Infections amongst private manufacturing personnel unaware of risks	No
	Absence of testing record to confirm receipt of correct candidate vaccine	No
	Inconsistencies in downstream testing results	No
R&D	Weaponization (clear intent) research and scale-up of agents	Partially
	Signature identification through microbial forensics	No
	Specific vaccination campaigns differing from standard vaccine strains	No
Equipment & Facilities	Construction of high/maximum containment facilities	No
	Construction of small and dual-use facilities	No
	Clarity of organizational structure at high/maximum containment facilities	Yes*2
	High/maximum containment facilities funded by military budget	Yes*2
	Equipment procurement outsourced to contractors	No
	Import/manufacture of equipment on AG control list, e.g., peptide synthesis machines	No
	Biological simulation platforms (machine learning, cloud labs)	No
	Large freezers to store viruses and genetic material	No
	Single-use plastic incubators, shaker flasks, small bioreactors	No
	PCR/qPCR	No
Materials	Pathogenic agents (Influenza virus, mammalian or avian)	Yes*2,*3
	Mammalian cell culture or fertilized chicken eggs	No
	Materials for genetic editing & synthesis	No
	Materials for mRNA vaccine production	No
	Microparticles/nanospheres for delivery	No
	Animal models (primate or small mammal)	No
Expertise & Human Resources	Academic research on high-risk pathogenic agents (including sudden cessation of publications)	Yes*4
	Expertise on vaccine process engineering, virology, toxicology, molecular biology, epidemiology, immunology	Yes*2
	Delayed or less frequent publications	No
Defense & Military	Small elite military squadrons linked to R&D or intelligence services	No
	Changes to budget allocations for R&D/CBRN	Yes
	Changes to frequency and scope of CBRN exercises	No
	Mass military vaccination campaigns	No

'Yes' is identified in cases where the CBMs have the potential to capture the observable sign

*1 Only for vaccines for human use, and not related to scale-up

*2 Only P4/BL4 or biodefense relevant pathogens/facilities/staff are captured in CBMs

*3 While CBMs may capture research with a certain strain of influenza if it takes place in a high containment facility, it is unlikely to capture all research involving this pathogen.

*4 CBMs capture the publication policy for national biological defense research programs, but the scope is limited and does not involve publication surveillance.

Table 4: Observable signs of potential offensive capabilities in Scenario C

	Observables	Captured in CBMs?
Dual-use divergences	Unusual production patterns of food and beverage industries	No
	Choice of spore producing biopesticides (e.g., B. thuringiensis)	No
R&D	Use of B. anthracis and ricin in R&D activities	Yes
	Medical imports of non-vaccine strains of B. anthracis	No
	Scientists studying biopesticides who later disappear	No
Equipment & Facilities	Construction of high/maximum containment facilities	No
	High/maximum containment facilities funded by military budget	Yes*[1]
	Clarity of organizational structure at high/maximum containment facilities	Yes*[1]
	Remote locations of high/maximum containment facilities	Yes*[1]
	Abnormally high security at high/maximum containment facilities	No
	Import/manufacture of equipment on AG control list	No
	Castor oil production with cold pressing	No
	Pharmaceutical grade milling machine	No
	Integrated containment systems in equipment or operation under high-containment protocols	Yes
	Full-body PPE	Yes*[1]
	Sprayer tanks	No
	155-mm shells	No
	Microneedles	No
	Centrifuge with in-situ sterilization	No
	Uncrewed aerial vehicles for dispersal	No
	Flow filtration	No
Materials	Pathogenic agents	Yes*[1]
	Growth of castor beans	No
	Ammonium sulfate	No
	Research on B. anthracis when endemic in the country's soil	No
	Use of solvents that enhance dermal absorption	No
	Kinases	No
	Small mammals for field-testing	No
Expertise & Human Resources	Academic research on high-risk pathogenic agents (including sudden cessation of publications)	Yes*[2]
	Inoculation of wild-type bacterial strains from samples	No
	Fermentation knowledge from the dairy/beverage industry	No
	Expertise on toxicology	Yes*
Defense & Military	Small elite military squadrons linked to R&D or intelligence services	No
	Emphasis on UAVs	No
	Prophylactic stockpiling	No
	Denial of access to certain open areas (possible field testing)	No

'Yes' is identified in cases where the CBMs have the potential to capture the observable sign

*[1] Only P4/BL4 or biodefense relevant pathogens/facilities/staff are captured in CBMs

*[2] CBMs capture the publication policy for national biological defense research programs, but the scope is limited and does not involve publication surveillance.

Table 5: Collated data on CBM capture of identified observable signs across common and scenario-specific observables

Common observables across the three scenarios:

3/21 or 14% captured | 8/21 or 38% partially captured | 10/21 or 48% not captured

- 3 observables captured and 7 observables partially captured, out of a total of 14 'R&D' observables
- Only 1observable partially captured and no observables fully captured out of a total of 5 'diplomatic engagement' observables
- No observables captured out of a total of 2 'public sentiment & internal shifts' observables

Observable signs from Scenario A:

10/35 or 29% captured | 0/35 or 0% partially captured | 25/35 or 71% not captured

With common observables added (10/35 + 3/21 = 13/56) = 23% captured

With common observables added (0/35 + 8/21 = 8/56) = 14% partially captured

With common observables added (25/35 + 10/21 = 35/56) = 63% not captured

- No observables captured out of a total of 7 'dual-use divergences in large-scale manufacturing' observables
- 5 observables captured out of a total of 12 'equipment & facilities' observables
- 2 observables captured out of a total of 7 'materials' observables
- 2 observables captured out of a total of 3 'expertise & human resources' observables
- Only 1 observable captured out of a total of 6 'defense & military' observables

Observable signs from Scenario B:

7/34 or 21% captured | 3/34 or 8% partially captured | 24/34 or 71% not captured

With common observables added (7/34 + 3/21 = 10/55) = 18% captured

With common observables added (3/34 + 8/21 = 11/55) = 20% partially captured

With common observables added (24/34 + 10/21 = 34/55) = 62% not captured

- Only 1 observable captured, and 2 observables partially captured, out of a total of 8 'dual-use divergences' observables
- Only 1observable partially captured and no observables fully captured out of a total of 3 'R&D' observables
- 2 observables captured out of a total of 10 'equipment & facilities' observables
- Only 1 observable captured out of a total of 6 'materials' observables
- 2 observables captured out of a total of 3 'expertise & human resources' observables
- Only 1 observable captured out of a total of 4 'defense & military' observables

Observable signs from Scenario C:

9/36 or 25% captured | 0/36 or 0% partially captured | 27/36 or 75% not captured

With common observables added (9/36 + 3/21 = 12/57) = 21% captured

With common observables added (0/36 + 8/21 = 8/57) = 14% partially captured

With common observables added (27/36 + 10/21 = 37/57) = 65% not captured

- No observables captured out of a total of 2 'dual-use divergences' observables
- Only 1observable captured out of a total of 3 'R&D' observables
- 5 observables captured out of a total of 16 'equipment & facilities' observables
- Only 1 observable captured out of a total of 7 'materials' observables
- 2 observables captured out of a total of 4 'expertise & human resources' observables
- No observable captured out of a total of 4 'defense & military' observables

An essential element for verification or compliance assessment judgements

The CBMs were adopted as an interim measure to enhance confidence in treaty compliance and to improve peaceful international co-operation. The mechanism was never intended as a verification or compliance assessment tool. It is therefore not surprising that roughly fifty to seventy-five per cent of the observable signs of potential offensive capabilities identified in the project scenarios were not captured in the CBMs. Moreover, several decades have passed since the information to be exchanged in the CBM modalities was agreed and there have been significant socio-political and scientific changes since, which limit the relevance of some, though by no means all, of the information requested.

The information exchanged through the CBM mechanism should be viewed primarily as a tool for demonstrating responsible behavior (Kelle and Dando, 2025), and not as a tool for verifying technical capabilities. However, what the project data also demonstrates is that roughly twenty-five to fifty percent of the observable signs of potential offensive capabilities identified in the scenarios were actually captured or partially captured in the CBMs. This underscores that a significant chunk of the information exchanged through the CBM mechanism—if provided accurately, regularly, and in sufficient detail—is relevant to providing a picture of technical capabilities. The CBMs can build up this picture over time, thereby establishing a country-specific baseline of normal capabilities and activity, essential for any verification or compliance assessment judgement.

There are, of course, aspects of the current modalities that can be improved or that need clarification. CBM Form A (Part 2 (i)), which calls for information on national biodefense research programs, should, for example, be amended to clarify that the request for information includes both military and civilian biodefense research programs. The requirement should be to declare any facilities and programs, whether in government, industry or academia, that are engaged in activities to counter deliberate outbreaks of disease or uses of toxins in humans, animals or plants. Requests for additional information could also be added to the current modalities, on for example, treatment of waste streams, refrigeration and levels of security. There are several broad areas of information-sharing that could be added in an amended or new modality. These include diplomatic engagement as well as public sentiment and internal shifts.

Notwithstanding the potential for updating and expanding the CBMs, they form an important element of a verification and compliance assessment process. While the only current mechanism the BWC has for capturing observable signs is the CBM mechanism, there have been other efforts to capture observable signs, most obviously through the work of the VEREX group. The following chapter considers the work of VEREX and how the observable signs identified in the project link to the measures and tools VEREX identified.

Chapter 5

Revisiting VEREX for Compliance Monitoring

This chapter considers the verification approaches proposed by the Verification Experts Group (VEREX), against the sets of observables identified by this project.

Contextualizing VEREX

At the Third Review Conference (September 1991) of the Biological Weapons Convention States Parties decided to establish an Ad Hoc Group of Governmental Experts, open to all States Parties, to identify and examine potential verification measures from a scientific and technical standpoint. This Verification Experts Group (VEREX) held four sessions in Geneva between March 1992 and September 1993[1] and identified 21 potential measures and submitted its report to all States Parties for consideration. The mandate of the Group was broad, in that it had to:

- Identify and examine potential verification measures from a scientific and technical standpoint and seek to identify measures which could determine:
  - Whether a State Party is developing, producing, stockpiling, acquiring or retaining microbial or other biological agents or toxins, of types and in quantities that have no justification for prophylactic, protective or peaceful purposes;
  - Whether a State Party is developing, producing, stockpiling, acquiring or retaining weapons, equipment or means of delivery designed to use such agents or toxins for hostile purposes or in armed conflict.

Measures could be addressed singly or in combination and measures were evaluated in a manner that took account of the broad range of types and quantities of microbial or other biological agents, including toxins, whether naturally occurring or altered which are capable of being used as a means of warfare.

The Group examined potential measures using six main criteria.

- Their strengths and weaknesses based on, but not limited to, the amount and quality of information they provide, and fail to provide;
- Their ability to differentiate between prohibited and permitted activities;
- Their ability to resolve ambiguities about compliance;
- Their technological, material, labor (personnel) and equipment requirements;
- Their financial, legal, safety and organizational implications;
- Their impact on scientific research, scientific cooperation, industrial development and other permitted activities, and their implications for the confidentiality of commercial proprietary information.

1 30 March–10 April 1992; 23 November–4 December 1992; 24 May–4 June 1993; and 13–24 September 1993

The process was dynamic. Although the final report noted 21 measures were initially identified, the measure "notifications" does not appear in the final evaluation tables, whereas exchange visits were considered as both an on-site and an off-site measure.

Table 1 provides an overview of the measures identified and evaluated by VEREX, according to the final report.

Table 1: VEREX measures

	Measures identified and evaluated by VEREX	Definition of measure (as per VEREX report)
Off-site Measures	**Information Monitoring**	
	Surveillance of publications	Selective scanning and analysis of publicly available printed matter and of the media with special attention to scientific literature related to activities in the biological field.
	Surveillance of legislation	Collecting and analyzing information with regard to legislation that exists in relation to the BWC or other areas of interest.
	Data on transfers, transfer requests and production	Collection and analysis of national export and import data, available or specifically requested, government and industrial production statistics, culture collection records and similar information. There may or there may not be an agreed standard for the availability of the nature of the information.
	Multilateral information sharing	The use of any voluntary international provision or exchange of information on medical, veterinary, agricultural, environmental safety standards, defense and waste management issues, etc., relating to materials and activities of potential relevance to the BWC. Such information sharing on a voluntary basis may or may not have an agreed standard for the nature of the information to be provided.
	Exchange visits (off-site)	Visits of experts arranged for scientific purposes by one country to comparable facilities of another country (States Parties) under bilateral or multilateral agreements. Exchange visits need not be restricted to declared facilities.
	Data Exchange	
	Declarations	Mandatory, periodic reporting on a regular basis of information considered to be of relevance for verification of the BWC. The nature of the events/items/facilities to be declared has yet to be fully defined. Notifications were considered to be a subset of declarations, concerned with the reporting of new or unforeseen events or forecast of events in order to pre-empt compliance concerns.
	Notifications	
	Remote Sensing	
	Surveillance by satellite	A variety of techniques operated by an artificial body placed in orbit around the earth or other planet that enable, to varying degrees, the detection, description, measurement or identification of some property of an object of interest without actually coming into physical contact with the object.
	Surveillance by aircraft	A variety of techniques operated by crewed and uncrewed aerial vehicles, including airplanes, helicopters, airships and balloons that enable, to varying degrees, the detection, description, measurement or identification of some property of an object of interest without actually coming into physical contact with the object.
	Ground-based surveillance (off-site)	Surveillance of a site of interest at some agreed perimeter surrounding a site or many kilometers distance either by remote sensing or by visual inspection

	Measures identified and evaluated by VEREX	Definition of measure (as per VEREX report)
	Inspections	
	Sampling and identification (off-site)	To take samples of the area in the vicinity of a declared or undeclared facility without penetrating its boundary.
	Observation (off-site)	Monitoring a site to get a sense of activities being carried out in the facility and also to get acquainted with the external characteristics of the facility.
	Auditing (off-site)	The critical examination, outside a facility boundary, in accordance with agreed standards and criteria, of documentary records, electronically held data and manuals, to assess consistency of matters recorded and material account with declared purposes and permitted activity.
On-Site Measures	**Exchange visits**	
	International arrangements	Visits of experts arranged for scientific purposes by one country to comparable facilities of another country (States Parties) under bilateral or multilateral agreements. Exchange visits need not be restricted to declared facilities
	Inspections	
	Interviewing	One of the measures of fact-finding for on-site inspection. It is conducted with the personnel of the site. The objective is to gain information about the nature, scale and scope of the activities and also to assess the overall function of the site.
	Visual inspections	Aimed at acquiring a general view of the site, facilities, equipment, materials and the degree of protection, safety measures and the peaceful activities which are being carried out. It includes taking note of the specificities and the characteristics of the equipment and the instruments.
	Identification of key equipment	An essential part of identification of key equipment on site is to confirm a facility's declaration and help to ensure that the equipment is not used for prohibited activities.
	Auditing (on-site)	The examination within a facility boundary, in accordance with agreed standards and criteria, of documentary records, electronically held data and manuals, to assess consistency of matters recorded and materials accounted with declared purposes and permitted activity.
	Sampling and identi-fication	The act of taking samples on the inspected site, analyzing these samples either on the site using appropriate methods or to transfer these samples from the site for identification or further investigation in appropriate laboratories.
	Medical examination	The collection of information about the activities of a facility by auditing medical and occupational health records of the work force; examination of recent and past cases of diseases; taking and analyzing body fluids and other clinical materials; and surveying the immunological status of the work force versus epidemiological background data
	Continuous Monitoring	
	By instruments	Activity conducted on a continuing basis using devices or instruments with the specific role of monitoring ongoing processes, parameters or agents, occurring in key equipment of a particular facility, and/or storage rooms or special storage facility, or testing areas.
	By personnel	Activity conducted on a continuing basis using observers or other highly qualified experts with the specific role of monitoring ongoing processes, parameters or agents, occurring in key equipment of a particular facility, and/or storage rooms or special storage facility, or testing areas.

The VEREX Report and the Ad Hoc Group

Upon the submission of the report States Parties met at a Special Conference to review the report and decide on any next steps. The Special Conference established the mandate of the Ad Hoc Group to "consider appropriate measures, including possible verification measures, and draft proposals to strengthen the Convention, to be included, as appropriate, in a legally binding instrument" for the States Parties to consider.

The AHG met over 24 sessions between 1995 and 2001, totaling 330 days of work.

As Table 2 notes, of the more than 20 measures identified by VEREX, some measures appear as both on-site and off-site measures, and 16 were included in the BWC protocol Chair's text (the composite text).

Those not included were relatively intrusive (e.g., surveillance by satellite or aircraft, off-site ground-based surveillance, off-site sampling and analysis and continuous monitoring.) By the time the Ad Hoc Group was completing its work, the experience of UNSCOM and other political developments had reduced the appetite for intrusive, multilateral disarmament regimes.

The checklist approach in the table, however, masks other approaches and issues that are important (e.g., what is declared, what kind of data is requested), including how techniques such as sampling and analysis and interviewing can be used effectively in a cooperative and uncooperative environment. The table is, therefore, not a complete picture of how the discussions and measures from VEREX transferred or translated into the AHG's text of early to mid-2001.

Table 2: VEREX measures and their inclusion in the AHG text.

VEREX measure	In Composite Text
Information Monitoring	
Surveillance of publications	✓
Surveillance of legislation	✓
Data on transfers, transfer requests and production	✓
Multilateral information sharing	✓
Exchange visits (off-site)	✓
Data Exchange	
Declarations	✓
Notifications	✓
Remote Sensing	
Surveillance by satellite	
Surveillance by aircraft	
Ground-based surveillance (off-site)	
Inspections	
Sampling and identification (off-site)	
Observation (off-site)	✓
Auditing (off-site)	✓
Exchange Visits	
International arrangements	✓
Inspections	
Interviewing	✓

VEREX measure	In Composite Text
Visual inspections	✓
Identification of key equipment	✓
Auditing (on-site)	✓
Sampling and identification	✓
Medical examination	✓
Continuous Monitoring	
By instruments	
By personnel	

VEREX and the observables lists

Table 3: Common observable signs of potential offensive capabilities across the three scenarios

	Observables	Captured in VEREX?
R&D	Unusual levels of integration between defensive research projects	Yes
	Same funding stream directed to labs working on gain-of-function experiments and aerosol dissemination modelling	Yes
	Scientists and facilities overlapping in animal testing, formulation, and stabilization steps	Yes
	Work with animal models and nonhuman primates in experimental programs	Yes
	Aerosolization in static or dynamic test chambers	Yes
	Unusual outbreaks	Yes
	Deaths at relevant facilities (of relevant scientists)	Partially
	Biosafety accident reporting	Partially
	Reports of clandestine field-testing locations or large imports of nonhuman primates	No
	Ex-bioweaponeers moving to foreign labs	No
	Refrigeration at military storage sites	Yes
	Lack of transparency when asked about dual-use activities and capabilities	Yes
	Linkages between pharma company and military complex	Yes
	Animal testing which cannot be corroborated by published literature	Yes
Diplomatic Engagement	Abuse/bad faith engagement with arms control and non-proliferation forums (BWC, UNSGM, WHO, WOAH, FAO, UNSCR)	No
	Disinformation, delaying tactics or disruption of substantive decisions in arms control and non-proliferation forums	No
	Vetoing UNSC resolutions	No
	Lack of transparency during consultations	No
	Accusations of other states possessing a bioweapons program	No
Public Sentiment & Internal Shifts	Shifts in public opinion on biological and chemical weapons	No
	Buzz on social media and in news media about specific facilities	No

Table 4: Observable signs of potential offensive capabilities in Scenario A

	Observables	Captured in VEREX?
Dual-use divergences in large-scale manufacturing	Non-attenuation of viruses/non-modification or gene drives of bacteria to select for prime antibiotic traits	Yes
	Purchase of reagents (growth media, serums, buffers, etc.) not in line with standard manufacturing practices	Yes
	Missing or conflicting records of operations	Yes
	Mothballed but still-working equipment in pharmaceutical facilities	Yes
	Overly thorough treatment of waste streams	Yes
	Use of disposable plastic jackets and piping for fermentation vessels	Yes
	Stringent containment during downstream processing	Yes
Equipment & Facilities	Construction of high/maximum containment facilities	Yes
	Clarity of organizational structure at high/maximum containment facilities	Yes
	High/maximum containment facilities funded by military budget	Yes
	High/maximum containment facilities built by a private company	Yes
	Remote locations of high/maximum containment facilities	Yes
	Abnormally high security at high/maximum containment facilities	No
	Bio-pesticide production facility with high-level containment measures	Yes
	Very high energy usage (freezers) at high/maximum containment facilities	No
	Import/manufacture of equipment on AG control list	Yes
	Crop sprayers	Yes
	Process control software and instrumentation	Yes
	Cryogenic freezers (under -80C)	Yes
Materials	Pathogenic agents (*Yersinia pestis, Francisella tularensis, Vibrio cholerae, Clostridium botulinum*)	Yes
	Known strains in country possession	Yes
	Materials/agents purchased from commercial providers if used in legitimate research	Yes
	Materials/agents illicitly acquired through unofficial networks	No
	Research on high-risk pathogenic agents in areas where these pathogens are endemic	Yes
	Additives for encapsulation of probiotics	Yes
	Animal models (primate or small mammal)	Yes
Expertise & Human Resources	Academic research on high-risk pathogenic agents (including sudden cessation of publications)	Yes
	Lack of public job postings for relevant sites	No
	Expertise on dispersion modelling, simulation, toxicology, drug delivery, etc.	Yes
Defense & Military	Small elite military squadrons linked to R&D or intelligence services	No
	Changes to budget allocations for R&D/CBRN	Yes
	Government tender sites calling for pharmaceutical industry support	No
	Changes to frequency and scope of CBRN exercises	Yes
	Mass military vaccination campaigns	Yes
	Prophylactic stockpiling (e.g., antibiotics)	Yes

'Yes' is identified in cases where a VEREX measure or category have the potential to capture the observable sign

Table 5: Observable signs of potential offensive capabilities in Scenario B

	Observables	Captured in VEREX?
Dual-use divergences	Extensive dual-use R&D capability (with potential for concealment of offensive activities)	Yes
	Extensive later stage dual-use capability (with potential for concealment of offensive activities)	Yes
	Personnel unaware of offensive nature of their work	No
	Civilian organizations (sub-contractors) unknowingly involved in offensive activities	Partially
	Use of private vaccine manufacturers of viral agents	Yes
	Infections amongst private manufacturing personnel unaware of risks	Yes
	Absence of testing record to confirm receipt of correct candidate vaccine	Yes
	Inconsistencies in downstream testing results	Yes
R&D	Weaponization (clear intent) research and scale-up of agents	Partially
	Signature identification through microbial forensics	Yes
	Specific vaccination campaigns differing from standard vaccine strains	Yes
Equipment & Facilities	Construction of high/maximum containment facilities	Yes
	Construction of small and dual-use facilities	Yes
	Clarity of organizational structure at high/maximum containment facilities	Yes
	High/maximum containment facilities funded by military budget	Yes
	Equipment procurement outsourced to contractors	No
	Import/manufacture of equipment on AG control list, e.g., peptide synthesis machines	Yes
	Biological simulation platforms (machine learning, cloud labs)	Yes
	Large freezers to store viruses and genetic material	Yes
	Single-use plastic incubators, shaker flasks, small bioreactors	Yes
	PCR/qPCR	Yes
Materials	Pathogenic agents (Influenza virus, mammalian or avian)	Yes
	Mammalian cell culture or fertilized chicken eggs	Yes
	Materials for genetic editing & synthesis	Yes
	Materials for mRNA vaccine production	Yes
	Microparticles/nanospheres for delivery	Yes
	Animal models (primate or small mammal)	Yes
Expertise & Human Resources	Academic research on high-risk pathogenic agents (including sudden cessation of publications)	Yes
	Expertise on vaccine process engineering, virology, toxicology, molecular biology, epidemiology, immunology	Yes
	Delayed or less frequent publications	No
Defense & Military	Small elite military squadrons linked to R&D or intelligence services	No
	Changes to budget allocations for R&D/CBRN	Yes
	Changes to frequency and scope of CBRN exercises	Yes
	Mass military vaccination campaigns	Yes

'Yes' is identified in cases where a VEREX measure has the potential to capture the observable sign

Table 6: Observable signs of potential offensive capabilities in Scenario C

	Observables	Captured in VEREX?
Dual-use divergences	Unusual production patterns of food and beverage industries	No
	Choice of spore producing biopesticides (e.g., B. thuringiensis)	Yes
R&D	Use of B. anthracis and ricin in R&D activities	Yes
	Medical imports of non-vaccine strains of B. anthracis	Yes
	Scientists studying biopesticides who later disappear	No
Equipment & Facilities	Construction of high/maximum containment facilities	Yes
	High/maximum containment facilities funded by military budget	Yes
	Clarity of organizational structure at high/maximum containment facilities	Yes
	Remote locations of high/maximum containment facilities	Yes
	Abnormally high security at high/maximum containment facilities	No
	Import/manufacture of equipment on AG control list	Yes
	Castor oil production with cold pressing	Yes
	Pharmaceutical grade milling machine	Yes
	Integrated containment systems in equipment or operation under high-containment protocols	Yes
	Full-body PPE	Yes
	Sprayer tanks	Yes
	155-mm shells	No
	Microneedles	Yes
	Centrifuge with in-situ sterilization	Yes
	Uncrewed aerial vehicles for dispersal	No
	Flow filtration	Yes
Materials	Pathogenic agents	Yes
	Growth of castor beans	Yes
	Ammonium sulfate	Yes
	Research on B. anthracis when endemic in the country's soil	Yes
	Use of solvents that enhance dermal absorption	Yes
	Kinases	Yes
	Small mammals for field-testing	Yes
Expertise & Human Resources	Academic research on high-risk pathogenic agents (including sudden cessation of publications)	Yes
	Inoculation of wild-type bacterial strains from samples	Yes
	Fermentation knowledge from the dairy/beverage industry	No
	Expertise on toxicology	Yes
Defense & Military	Small elite military squadrons linked to R&D or intelligence services	No
	Emphasis on UAVs	No
	Prophylactic stockpiling	Yes
	Denial of access to certain open areas (possible field testing)	No

'Yes' is identified in cases where a VEREX measure has the potential to capture the observable sign

How VEREX categories fit in other verification and compliance regimes

There is no shortage of compliance, verification, inspection or investigation regimes from which any future BWC regime can draw experience and lessons from. Since 1991, when the Third Review Conference established VEREX, the Trilateral Process between Russia, the United States and the United Kingdom, the United Nations Special Commission (UNSCOM) and the United Nations Monitoring, Verification and Investigation Commission, the Ad Hoc Group, the efforts to wind up the Project Coast, the experience with dismantling Libya's weapons of mass destruction programs, updating and strengthening the United Nations Secretary General's Investigation Mechanism (UNSGM), the work of the Organization for the Prohibition of Chemical Weapons related to the implementation of the Chemical Weapons Convention and its work in Syria, the work of the World Health Organization in its attempts to establish the origins of the COVID pandemic and two formal consultative meetings of the BWC are directly relevant to any future work on compliance and verification.

In addition to these mechanisms and procedures, other examples beyond chemical and biological weapons remain valuable points of reference, including, but not limited to: UN Sanctions Committee reports related to the Democratic People's Republic of Korea (DPRK), the International, Impartial and Independent Mechanism of the United Nations related to Syria, the Universal Periodic Review of the Human Rights Council, and the assessment of implementation of anti-money laundering and terrorism finance completed by the Financial Action Task Force.

There is also a wealth of domestic experience with biological safety and security from which relevant experience and information can be drawn.

Table 7 uses VEREX's categories to identify a process, procedure or approach in an inspection or investigation that is identified in manuals, frameworks, or reports. The studies used are:

- United Nations General Assembly: 2013. Report of the United Nations Mission to Investigate Allegations of the Use of Chemical Weapons in the Syrian Arab Republic on the alleged use of chemical weapons in the Ghouta area of Damascus on 21 August 2013. A/67/997-S/2013/553, 16 September 2013
- Organization for the Prohibition of Chemical Weapons: 2023. Third report by the OPCW investigation and identification team pursuant to paragraph 10 of decision c-ss-4/dec.3 "addressing the threat from chemical weapons use" Douma (Syrian Arab Republic) – 7 April 2018. S/2125/2023. 27 January 2023
- World Health Organization: 2024. Global framework to define and guide studies into the origins of emerging and re-emerging pathogens with epidemic and pandemic potential. Geneva: World Health Organization.

These reports are not intended to demonstrate what is most effective or required for a compliance and verification mechanism for the BWC or to evaluate the relevance of any measure or category or measures from VEREX to other mechanisms. As with Table 2 on the Ad Hoc Group, the identified VEREX measures in other areas are indicative of the relevance of the measures to compliance and verification.

The examples here are all extraordinary. If, for example, routine CWC activity was identified, most of the measures would be covered. In addition, the standard operating procedures address a number of issues often identified with a measure: i.e., how would it work. This is evident with sampling and analysis and the permitted techniques and procedures for the collection and use of samples and the procedures for their analysis.

Table 7: Examples of techniques and procedures used in other compliance and verification agreements

VEREX categories and measures	UN mission to investigate allegations of use of chemical weapons (August 2013)	OPCW Investigation and Identification Team (April 2018)	WHO Global Framework
Information Monitoring and Data Exchanges			
Surveillance of publications	✓	✓	✓
Surveillance of legislation			✓
Data on transfers, transfer requests and production			✓
Multilateral information sharing	✓	✓	✓
Exchange visits (off-site)		✓	✓
Declarations			✓
Notifications		✓	✓
Remote Sensing and Continuous Monitoring			
Surveillance by satellite		✓	
Surveillance by aircraft			
Ground-based surveillance (off-site)			✓
By instruments			
By personnel			
Inspections (Off Site and On Site)			
Sampling and identification (off-site)	✓	✓	✓
Observation (off-site)			
Auditing (off-site)		✓	
Exchange Visits International arrangements	✓	✓	✓
Interviewing	✓	✓	✓
Visual inspections	✓	✓	✓
Identification of key equipment	✓	✓	
Auditing (on-site)			
Sampling and identification	✓	✓	✓
Medical examination	✓	✓	✓

VEREX and the BWC Working Group

Following the end of the negotiations on the Protocol in 2001 two decades passed before a structured review of compliance and verification issues was placed back on the working agenda of the States Parties. This occurred following a decision of the ninth review conference in 2022 to establish a working group.

Unlike in VEREX, the working group has to date relied mainly on working papers and discussions in sessions dedicated to each topic to identify any measures and procedures that could be of value to strengthening the Convention.

As noted in the rolling text by the Chair of the Working Group on Strengthening the Convention (28 July, 2025), any "methods, procedures and techniques related to compliance and verification should be able to provide in a timely, effective and efficient fashion, credible evidence of compliance or non-compliance …and the development of compliance and verification measures should be without prejudice to national security, sustainable development, technological, economic or development interests of States Parties." In addition, the rolling text identifies the following:

- Both on-site and off-site approaches to verification that are practicable, feasible and proportionate;
- The value of mandatory declarations;
- Complementarity between any proposed compliance and verification measures, noting that combinations of measures could improve the possibility of providing credible evidence of compliance or non-compliance;
- Potential investigative measures able to rapidly and credibly look into allegations concerning possible non-compliance, balancing effective measures with the protection of sensitive national security and confidential proprietary rights.

VEREX and new scientific and technical developments

Given VEREX occurred 30-plus years ago, various calls for the exercise to be repeated have been made. There is no need to repeat VEREX from a scientific and technological standpoint.

VEREX measures were broad categories. Rather than assume that a new scientific or technological development since 1993 was not included in VEREX, it is more valuable to assess if a new capability or technique was not captured by one or more of VEREX's categories.

- Unpiloted aerial vehicles (i.e., drones) are clearly a platform for remote sensing and an addition to the identified surveillance by satellite and surveillance by aircraft.
- Whole gene sequencing, real-time PCR, peptide synthesizers, and nucleic acid synthesis technology all fit within, or are adjacent to, sampling and analysis.
- Open-source intelligence covers a wide array of possible techniques and procedures, but most are within the information monitoring category of VEREX.

As noted, VEREX identified a number of categories that remain relevant. Where these new developments fit into the VEREX categories offers insights of how a re-evaluation of VEREX might support the work of the Working Group.

Repeating VEREX, or something similar to VEREX, only has value if a socialization and awareness raising approach was required for States Parties on the types of broad categories of measures that might contribute to compliance monitoring and verification. It is correct to note more, and new, methods and procedures are available today, but the VEREX assessment criteria remains valid as a starting point to evaluate the advantages and limitations of any new technology or scientific process.

VEREX today

The categories of measures identified by VEREX remain valid today. In addition, the main criteria by which a measure was assessed also remain valid over 30 years since the report was concluded. VEREX looked at a potential measure broadly: e.g., declarations. It did not look at what types of declarations might be required or useful, the scope of those declarations, and how any declared information was to be provided, assessed and validated for accuracy and completeness. If, for example, a declaration was developed for specific types of equipment in use in maximum and high containment laboratories, this would require agreement not only on how to define a maximum containment laboratory and a high containment laboratory, but also the type of any equipment (e.g., fermenters) its size (e.g., above a certain threshold or range), and its material composition, to name a few.

How relevant any specific VEREX measure is depends on how any broad measure is developed into a specific measure that can provide timely, accurate and relevant information to States Parties. As such, VEREX remains a valid and useful starting point for additional work.

Chapter 6

Emerging Technologies for Compliance Monitoring

Introduction

The lack of a comparable, formal review of the technical options available for verification and compliance monitoring may mean that States Parties are approaching Working Group discussions with differing levels of understanding of the technologies and techniques that can be harnessed for compliance monitoring and verification. Certainly, in the three decades since VEREX issued its final report, science and technology, particularly in the life sciences, has progressed exponentially. As many have noted, this changes the possibilities and constraints for compliance monitoring, as well as possibly leading to significantly different assumptions underlying recommended compliance monitoring approaches from those voiced in the past (Walker, 2020; Revill, n.d.; Biosecure and IAP, 2016; Appleton et al., 2022; Revill et al., 2022).

Some reports have been issued by the UN Institute for Disarmament Research (UNIDIR), independent meetings of technical experts and non-governmental research organizations, in an attempt to fill this gap (or at least to prompt a more formal process for the review of the relevant science and technology within a formal BWC process). However, such a review, which could be incorporated into a broader S&T review mechanism, will entail an outlay of resources. Unfortunately, based on a statement issued at the conclusion of the fifth session of the Working Group and the stubborn position of a few State Parties of the need for a Special Conference, this is likely to be diplomatically difficult (*On a Special Conference and the ICA and S&T mechanisms*, 2024).

Thus, this chapter aims to contribute to a shared understanding by the diplomats discussing possible compliance monitoring approaches during the Working Group. It first summarizes the literature already present thus far on the most relevant technologies which have emerged since VEREX and discusses how they could contribute to compliance monitoring. It then addresses how suited such technologies and techniques would be for capturing the observables identified in chapter X, before concluding with a discussion of the full spectrum of compliance monitoring and which technologies are likely to become relevant at which points along that spectrum, from trust-building exercises to formal challenge inspections.

Technological Development Since VEREX

This section summarizes the most relevant technologies that have emerged since VEREX concluded in the early 1990's, as well as techniques (e.g., open-source intelligence, microbial forensics) which have developed when enabled by these novel technologies. It also discusses the maturity and reliability of these technologies or techniques, issues surrounding their certification and assurance for use in formal treaty contexts, and legal and political considerations including the sensitivity and classification of information generated and the intrusiveness of methods.

Digitalization of Data

While much of the recent literature on scientific and technological developments relevant to compliance monitoring under the BWC focuses on those which are still considered emerging in the present day, a few have noted that most of the online databases we take for granted today were not available

when VEREX discussions concluded. This includes databases of publications such as Google Scholar, PubMed, Web of Science; and of trade data, including publicly available (e.g., UN ComTrade) and subscription-based databases of third-party commercially supplied data (e.g. Export Genius and Sayari) (Revill, n.d.).

While the final VEREX report indicates the need for a computer for surveillance of publications, legislation, and data on transfers, transfer requests and production, it does not predict the ease of access to digital databases that would be possible only a decade later. The closest it comes is suggesting that "the possibility of establishing [a computerized] international data base should be considered" (Ad Hoc Group of Governmental Experts to Identify and Examine Potential Verification Measures from a Scientific and Technical Standpoint, 1993).

The migration of most datasets online has been a step-change in widespread access to information. This has given rise to approaches such as OSINT, as well as enabled technologies requiring the transmission of massive sets of information, such as satellite-based sensing, epidemiological models, and bioinformatics (all discussed in more detail below). Digital data is now the default, and any compliance monitoring under the BWC designed today would include it automatically.

Satellites and Satellite-Based Sensors

The Open Skies Treaty, which was signed in 1992, lends a good picture of the level of technological development considered suitable for multilateral monitoring at the time, with resolution limits carefully selected so as to not reveal information which would pose a national security risk, yet still enabling parties to observe each other's movements of conventional forces. Aircraft conducting observation flights under the treaty could use optical and video cameras with a ground resolution of 30 centimeters, infra-red line-scanning devices with a ground resolution of no better than 50 centimeters, and synthetic aperture radar (SAR) with a ground resolution of no better than 3 meters ('TREATY ON OPEN SKIES', 2002).[1]

Some electro-optical imagery was commercially available at the time,[2] but it had a ground sampling distance (GSD)[3] of 5–10 meters. Today, commercial satellite imagery providers can supply imagery with a GSD of 30 centimeters (Hanham, 2020). And while the highest resolution images remain expensive for daily captures, 3-meter resolution images are available daily and enable monitoring that can 'cue' observers to collect higher resolution images if they detect changes to activity levels or structures (Planet Labs, n.d.). In October 2024, the Washington Post published a piece noting construction and expansion at a site that was associated with the past Soviet biological weapons program (Axe, 2024). Use of commercial satellite imagery such as this by independent observers in civil society could feed into consultations under Article V.

Most other types of satellite-based imagery were unavailable to the public, including infra-red/thermal, SAR, multi/hyperspectral, and radio frequency. In some cases, this was due to regulation prohibiting open access, as in the case of Landsat thermal imagery. In 2008, Landsat imagery was made publicly available ('Landsat Data Access | U.S. Geological Survey', n.d.). In addition to electro-optical, the US government-owned satellite constellation continues to provide thermal imagery with a resolution up to 100 meters (NASA, n.d.). However, much higher resolution commercial thermal imagery has recently become available through the UK-based private company SatVu, with resolution as high as 3.5 meters (SatVu,

1 Note that these resolution limits are for sensors on aircraft. The Open Skies Treaty does not deal with satellite observation. Overflights at a lower altitude could capture the same resolution as higher-resolution sensors on aircraft flying at higher altitude.

2 Such as the Spot 1 satellite, launched in 1986 and providing a ground resolution of 10m.

3 While not exactly the same, it can be thought of as the resolution (i.e., a GSD of 30cm means that each pixel on the imagery captures an area on the ground which is 30cm wide).

2023). In a reversal of the status quo in the late 2000's when Landsat archives became available, a commercial provider of thermal imagery is now providing US government agencies with access to its archives (SatVu, 2025).

Nonetheless, commercially available thermal imagery has yet to achieve the resolution which could unambiguously distinguish heat signatures within a facility. In late 2023, researchers used SatVu's high-resolution thermal satellite to observe two nuclear reactors at Yongbyon, North Korea, in an attempt to distinguish whether they were operating. While the images were able to distinguish changes in the heat signatures at the buildings housing the reactors, the strength of the heat signature did not match expectations and was theorized to be significantly affected by building construction materials (Park and Puccioni, 2024). Monitoring the thermal signatures of biological facilities will require more sensitivity than for nuclear reactors, and resolution will be an issue for determining exactly what areas are generating energy. At this stage, unless collected at a higher resolution (possibly entailing a sensor mounted on aircraft, rather than satellite), it is unlikely that thermal imagery will serve as more than contextual evidence for compliance monitoring, despite suggestions that thermal imagery could provide a heat signature that is compared with expectations of the number of staff believed to be on-site, types of processes, and levels of activity at a site (Appleton et al., 2022). Levels of site activity can be more easily detected on electro-optical imagery.

The first commercial SAR satellite was launched in 1995, providing resolutions ranging from 8 to 100 meters (NASA, n.d.; Liu, 2022). While more satellites with SAR capability were launched in the intervening two decades, the European Space Agency's launch of Sentinel-1 in 2014 marked a step-change in the accessibility of SAR. The data collected by Sentinel-1 was made freely available, which led to rapid development of satellites with higher resolution.[4] In 2018, two private companies (ICEYE and Capella Space) launched their own satellites (Liu, 2022). Both have continued launching satellites and growing their constellations and have achieved SAR resolutions up to 25 centimeters and 50 centimeters, respectively (Stringham et al., 2024; ICEYE, 2025).

Hyperspectral imagery has been described as performing spectroscopy of the Earth's surface (Hanham, 2020). It captures hundreds of wavelength bands invisible to the human eye, including in the visible, ultraviolet, near-infrared, and short-wave infrared spectrums. This generates data which lends itself well to processing with deep machine learning for determining features that classify and distinguish targets according to minute variations in their reflectance wavelengths, and the fusion of spectral and spatial data (Ferreira et al., 2024).

Unlike other remote sensors, which could provide useful information about facilities or activities of interest, or support on-site investigation planning, hyperspectral imagery can be directly used as a biological assay and is being developed as such. Rapid detection methods most commonly fall under immunological, nucleic acid, or biosensor-based assays; however, hyperspectral imagery presents a non-destructive alternative to these. Since 2009, hyperspectral has been demonstrated for detection of foodborne pathogens; although still comparatively new technology, its low cost, potential scalability and successful use thus far in experimental settings promise continuing innovation (Bonah et al., 2019). Hyperspectral has also been used to detect a variety of plant pathogens in seeds; while work continues on validating hyperspectral detection for more pathogens, it shares similar promise as a developing technology which could be taken advantage of in monitoring pathogen spread (Ferreira et al., 2024). While neither of these studies used satellite-based hyperspectral sensors, both airborne and satellite-based hyperspectral sensors exist and are under development for applications in monitoring crop health (Lu et al., 2020). In the near future, hyperspectral sensors should be able to not only monitor crop health but also provide a chemical analysis of materials on the ground, including material discharged as waste from facilities of concern (Hanham, 2020).

4 Sentinel-1 provides 10m resolution SAR. Open access to this data led to startups which explored applications for SAR data, but also drove commercial development of higher resolution SAR satellites.

Radio frequency (RF) sensors are at a lower level of readiness than other sensors but have recently been explored for their utility in detecting 'dark ships', vessels trying to evade detection by turning off or spoofing their automatic identification system (AIS). Large metal objects produce radio waves which can be picked up by a satellite-based RF sensor; ships emit particularly strong RF data, particularly on a large body of water. RF imagery can thus capture wide swaths of the ocean surface, as ships appear as very bright spots in the ocean. These positions can be compared to contemporaneous AIS data. If ships are not trying to conceal their location, their AIS position should be consistent with a dot on the RF image, and vice versa. If there is discrepancy, it could indicate the presence of a dark ship. These vessels are quite heavily associated with illegal transfers, either to port or ship-to-ship, and monitoring of AIS and RF data could be an approach to detecting potential transfers of material or equipment that is likely to go unreported in trade data (Turgeon, 2024). This data is still quite expensive, but there are commercial providers, including Kleos Space, Spire Global, Unseen Labs, and HawkEye 360. Some of the potential monitoring applications for SAR and thermal imagery to identify the operational status of facilities may eventually be possible with RF data as well.

Open-Source Intelligence (OSINT)

Open-source intelligence (OSINT) has been around since the start of World War II, and possibly much longer. However, widespread access to the internet has both increased the amount of open-source material available for analysis and provided an audience for this analysis. Although the acronym was around in the 1990's, it did not gain widespread traction until the 2010's (Block, 2023).

We generate data and share it online at an unprecedented rate, which continues to rise each year. The rise of social media platforms has encouraged this and thus become an important source for OSINT researchers. Of course, the increasing quantities of data also put constraints on human ability to verify and analyze it. This leads to what is colloquially known as 'information overload' and is an environment in which mis- and disinformation spreads rapidly. Artificial intelligence platforms may increase our ability to interpret such an expansive, heterogeneous, and constantly growing data pool (Wilton Park, 2022).

Increased access to satellite imagery has entailed its inclusion in OSINT methods, and the rise of geographic information systems (GIS) have streamlined the collection of geospatially tagged data. Google Earth is one of the best-known examples and provides free imagery from providers such as Maxar and Airbus. There are many other GIS-based platforms, ranging from subscription based, globally hosted where users can access existing datasets and imagery (e.g. ArcGIS) to free platforms to which users can add their own data (e.g. QGIS[5]).

Since the conclusion of VEREX, OSINT methods have been incorporated in the IHR, used to augment traditional verification by the OPCW Fact Finding Missions (FFMs) in Syria, and is used by the IAEA to assess Safeguards comprehensiveness (Revill et al., 2022). Some have suggested the utility of OSINT approaches for verifying the accuracy of CBM submissions, or to supplement material presented under future formal Article V consultations. In theory, this is something that an ISU with expanded resources and expertise could do (Cropper et al., 2022). However, without a mandate to use OSINT, the ISU may be loath to expose itself to the political backlash that can occur if it presents its own open-source analysis. Even the nature of the data it does collect could lead to accusations of bias towards either the accused or accusing party in a compliance dispute.

Nonetheless, OSINT can be a powerful tool for compliance monitoring, as it can pre-empt on-site inspections (politically difficult and resource intensive) with remote, informal monitoring to address compliance concerns at an earlier stage. Possible sources for monitoring inconsistencies include academic journals,

5 Used by IAEA country teams.

preprint servers, conference proceedings, public health reports, hospital admissions data, pharmaceutical sales information, patent databases, social media posts, trade data, company formations and government budget allocations related to biotechnology, and satellite imagery ('Project BEACON: Using OSINT methods in BWC verification – BlueDot Impact', n.d.). However, such processes can be abused to make bad faith accusations of non-compliance.[6]

This reinforces the noted need for additional verification of OSINT findings and thresholds for escalation to formal investigation (Suresh, n.d.) and could take some inspiration from the IAEA's approach, which uses a machine learning and natural language processing-based tool that examines open sources to identify activities that may be evading its formal Safeguards verification regime (Wilton Park, 2022). One former UNSCOM and UNMOVIC inspector noted that there is now enough information on past and on-going activities available on the internet to replace some of the functions of on-site inspections (Wilson and Smidovich, 2021).

Uncrewed Aerial Vehicles (UAVs)

By 1991, governments had already begun using UAVs for reconnaissance; they were used extensively in the Gulf War, which was contemporaneous with VEREX discussions (Haulman, 2003). However, UAVs were not commercially available until the mid-2000s, and this nascent industry did not fully emerge until the mid-2010s (Axon Enterprise, 2023).

UAVs present certain advantages over crewed aircraft. The financial costs of overflights and high-resolution satellite imagery was one issue of concern to VEREX (Meier, 2006). UAVs typically entail lower operating costs compared to crewed flights and conventional aircraft, as they carry lighter payloads and can be much smaller, thus consuming less fuel. They can also mitigate risks to inspectors while improving area access, for example enabling sample collection in a potentially contaminated area without exposing inspectors directly (Buse et al., 2022).

While satellite-based sensing can be done without the consent of the observed party, aircraft, even uncrewed, need permission for overflight (Meier, 2006). Thus, compliance monitoring with UAVs is likely to take place either under agreed-upon verification measures or in a highly contested environment.[7] However, the use of UAVs can mitigate some of the difficulties presented by weather such as cloud cover for satellite-based sensors. Many of the sensors discussed in the satellite-based sensor section above can be mounted on UAVs, so long as the UAV is large enough to handle the weight. Active sensors such as SAR and RF are much heavier, and electro-optical is the most common for small UAVs (i.e. cameras mounted on hobbyist drones). UAV-based sensors can also achieve a higher resolution due to a reduced distance to the target of monitoring.

UAVs are useful not only for capturing imagery but can also carry sensors for detecting particulates in air. VEREX experts had noted that drawing conclusions of compliance based on air samples from overflights would be difficult (Meier, 2006). The current state of technology would likely change this judgement. UAVs can fly at much lower altitude, collecting air samples where concentrations would be greater. The European Union has funded Project TeChBioT since 2022, which aims to develop a miniaturized gas chromatography-ion mobility spectroscopy (GC-IMS) tool which can be mounted on a vehicle and is supported by deep learning and artificial intelligence in its detection and identification of unique fingerprints of chemical and biological agents. This project is set to end in November 2025 (Home – Techbiot', n.d.).

6 For example, the Russian Federation presented hundreds of pages of 'evidence' including public patent filings and research publications to accuse the United States and Ukraine of non-compliance with the BWC in a long, drawn out Article V process that eventually invoked Article VI.

7 Take for example the use of UAV footage by Russia and Ukraine to accuse each other of the use of riot control agents on the battlefield, in violation of the CWC.

Biological Detection Methods and Microbial Forensics

Some of the most useful methods that would be used in case of on-site verification have progressed exponentially in the past three decades. While technologies such as biosensors and PCRs were around during VEREX, they were not easily used in a field environment, nor as well validated as they are today. Sanger sequencing was the main technology available for reading DNA. The Human Genome Project was just beginning, with a $3 billion investment to sequence a single human genome (the cost of sequencing a human genome today is well under $1,000) (Higgs, 2024; National Human Genome Research Institute, 2024).

Unlike nucleic-acid based identification techniques, biosensors work by measuring the reaction of a sample with receptors; some aspect of this reaction, such as pH change or heat generation, is converted into an electronic signal, which can then be processed and displayed on a user interface (Bhalla et al., 2016). Biosensors are selective, as the choice of receptors depends on the substance being detected. Advances in the range of agents that can be detected using biosensors and the ability to use them with a wider set of samples have been detailed in a 2016 report from an InterAcademy Partnership workshop. They note that sample preparation has become less complicated, with newer technologies making it unnecessary to separately desalinate and centrifuge samples in preparation, which eases the ability to prepare samples in the field. Integration of in-field biosensors with mobile applications which connect to remote databases also aids agent identification and management of data (Biosecure and IAP, 2016). All of these developments make biosensors easier to use in case of any on-site investigations. However, as they are limited by their specificity, the advantage of biosensors for compliance monitoring lies primarily in on-site investigations looking to detect the presence of a known set of pathogens. Each biosensor would likely need to undergo validation before use in formal verification activities.

VEREX noted that spectroscopic methods could not be used to uniquely identify biological substances (Ad Hoc Group of Governmental Experts to Identify and Examine Potential Verification Measures from a Scientific and Technical Standpoint, 1993). This is no longer the case. Since then, mass spectrometry-based methods have become increasingly relied upon for detection of microorganisms. Franco-Duarte et. al. (2019) give a comprehensive summary of the mass-spectrometry based and spectroscopic methods which are applicable for identification of bacteria and yeasts, alongside useful discussion of their reliability and considerations for selection of method. These include liquid chromatography-mass spectrometry (LC-MS), gas chromatography-mass spectrometry (GC-MS), matrix-assisted laser desorption/ionization-Time-of-Flight (MALDI-TOF MS), Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy, and Nuclear Magnetic Resonance (NMR) spectroscopy (Franco-Duarte et al., 2019). Specificity and sensitivity vary according to the method. Newer methods, such as MALDI-TOF MS and electron spray ionization (ESI MS), began to be developed in the 1980s and enabled the ionization of large biological molecules like proteins (previously, MS was limited to compounds which were more easily ionized, i.e. small molecules more commonly found in chemical agents) (Singhal et al., 2015). This was one of the key technological steps that would change the conditions underpinning VEREX's statement on the capability of spectroscopic methods. Spectroscopic methods are now widely used, particularly in protein analysis (ThermoFisher Scientific, n.d.).

The polymerase chain reaction (PCR) technique was first described in a journal article in 1985, and the first real-time PCR instrument was described in 1993, towards the end of VEREX meetings (ThermoFisher Scientific, n.d.; Development and Evolution of PCR', n.d.). PCR's primary function in detection is amplification; it replicates a target DNA sequence at an exponential rate by cleaving DNA strands, introducing primers at the ends of the DNA target region, then synthesizing new, complementary DNA strands using a heat-tolerant polymerase enzyme, before repeating the cycle by cleaving this new double strand of DNA. Because PCR requires a target DNA sequence in order to design a viable primer (although some slight mismatch between primer and template can be tolerated), it is not pathogen agnostic (Development and Evolution of PCR', n.d.). PCR will amplify whatever material is being looked for but will not flag non-target sequences.

Yet efforts are ongoing to improve universal detection using PCR: broad-range PCR (BRPCR) is a technology proposed as early as the 2000s which utilizes genetic features common across classes of organisms to design broad-based primers (Yang and Rothman, 2004). Yet today, it still has significant limitations: its use is currently limited to bacteria and fungi, for which there are appropriate unique yet universal genes to the class of organism; it is also more expensive than sequencing and has significantly lower sensitivity than conventional PCR (Li and Nakamura, 2022). Despite its universality shortcomings, PCR remains a highly cost-effective and field deployable technology for detection. And because it is so widely used, both in laboratory applications and public health, there are many pathogen-specific primers available. The 2015 IAP workshop highlighted the two-hour turnaround time of Cepheid's GeneXpert systems (Biosecure and IAP, 2016); the systems have continued to increase in speed. BioFire Defense purports to develop the fastest machines for real-time pathogen detection, using real-time PCR; they claim to deliver results in just over 15 minutes (BioFire Defense, 2025).

The cost of DNA sequencing has decreased massively, and the reads have become more accurate and detailed. At the time of VEREX, Sanger sequencing was the predominant sequencing technology. Now known as first-generation sequencing, this type was characterized by very low throughputs, which improved slightly with the introduction of automated capillary-based instruments in 1998. A step-change in sequencing capacity occurred in 2005 with the introduction of second-generation sequencing technology, which increased throughput by two orders of magnitude (Thompson and Milos, 2011). Second generation sequencing remains the most widely used today (Higgs, 2024). It works by fragmenting the DNA strand and then sequencing the segments in parallel, which can be as short as 30 nucleotides (Goldman and Domschke, 2014; Thompson and Milos, 2011). These fragmented sequence reads then must be re-assembled into a full genome read using bioinformatics approaches. Deep learning when applied to multi-omics data can identify complex patterns and harmonization can mitigate the challenges associated with integration of the disparate data (Higgs, 2024).

While the second-generation sequencing technologies are more widely used, third generation sequencing technologies which enable longer reads are a useful development for provision as legal evidence, as there is not as much reliance on compilation of the fragments by alignment algorithms back into a full genome (Appleton et al., 2022). However, third generation sequencing had previously lacked accuracy, with error rates as high as 10%. Nonetheless, both second and third generation sequencing have seen steady improvements in accuracy; third generation sequencing has begun to reach accuracy comparable to most second-generation methods, and some second-generation sequencing is reaching error rates as low as 1 in 10,000 bases (Higgs, 2024). Characterization of DNA modification (e.g. methylation) is now possible at a high level of detail, which can offer insights into possible alterations for microbial forensics work (Appleton et al., 2022).

Third generation sequencing was developing as early as 2010 but is still an emergent technology when it comes to detection and identification of proteins. Single-molecule sequencing simplifies sample preparation and raises consistency by eliminating amplification of DNA templates, which makes it useful for sequencing directly from samples (Thompson and Milos, 2011). It also has important benefits for proteomic sequencing, as a possible alternative to mass spectrometry (Higgs, 2024).

DNA sequencing speed has improved, but full genome sequencing remains difficult to do in the field. Most rapid DNA sequencing technologies rely on second generation methods such as capillary electrophoresis, which has a minimum analysis time of 90 minutes, and use non-portable equipment. However, in addition to improvements aimed at creating 'lab-on-a-chip' DNA probes, researchers are exploring third generation nanopore sequencing technology (Tytgat, 2022). Nanopore sequencing works be measuring the disruption of ion current as DNA strands are fed through a nanoscale pore, as each nucleotide affects the current slightly differently (Tytgat, 2022).

Metagenomics allows for direct testing of samples collected in the field without the need for isolating the DNA of interest, which allows for pathogen-agnostic identification (Revill et al., 2022). Analysis of wastewater samples collected during the Covid-19 pandemic to track outbreaks included metagenomic sequencing of the collected samples following filtration (Wurtz et al., 2023). There are different advantages to the use of second or third generation sequencing for metagenomic sequencing; third generation offers advantages in speed, but with tradeoffs in accuracy that can be significant enough to miss differentiation of genomes. Hybrid approaches, which use both second and third generation sequencing to cancel out these weaknesses, should be considered for any compliance-monitoring which utilizes sequencing technology.

Microbial forensics is a discipline which has emerged from improvements in sequencing technology and a recognized need for attribution of pathogen origin following the Anthrax letter attacks (Budowle et al., 2014; Schmedes and Budowle, 2019). This technique uses whole genome sequencing, bioinformatics, metagenomics, and mass spectrometry to identify signatures which differentiate strains and can indicate genetic engineering (Biosecure and IAP, 2016). This technique could theoretically be used to determine whether a pathogen is natural or has been modified (Cropper et al., 2022). An algorithm was developed in 2020 which could correctly identified a sequence's lab of origin in over half of trials, yet the code, which is publicly available, has seemingly not been updated since (Wang et al., 2021; treangenlab, 2021). The deteRNNT algorithm achieved a similar level of accuracy, and made use of recurrent neural networks on DNA motifs, phenotype information, and helped by attribution of the nation of origin (which, admittedly, is quite a lot of contextual information, more than could be expected in all possible use cases) (Cropper et al., 2022).

There are many considerations which must be addressed when using microbial forensics for attribution, and these were outlined even as the field of microbial forensics was developing (Budowle et al., 2014). To date, validation and certification to meet evidentiary standards remain an issue. Part of the reason is because the technologies upon which the technique relies are built for biological research purposes, not for investigations and forensic evidence collection (Appleton et al., 2022). The creation and maintenance of vast reference libraries is another, as well as achieving attribution algorithms which, despite being trained on known sequences, are still accurate when faced with unknown pathogens (Appleton et al., 2022). Machine learning algorithms which are trained to predict pathogenicity from genomic data tend to memorize the impact of mutations rather than understanding underlying biological mechanisms which lead to altered function (Wheeler, 2025).

Artificial Intelligence and Machine Learning

The foundations for the emergence of machine learning and artificial intelligence were set in the middle of the 20th century but did not reach a point of widespread development until the beginning of the 21st century with the advent of big data, parallel computing, and deep machine learning algorithms (Fradkov, 2020). Widespread public use of artificial intelligence has only emerged within the last few years.

The International Organization for Standardization defines artificial intelligence (AI) as "computer systems capable of performing tasks that typically require human intelligence, such as reasoning, learning, perception and language understanding" and distinguishes machine learning ML as a core capability enabling AI which "[enables] systems to analyze data, recognize patterns and make decisions without explicit programming" (International Organization for Standardization, n.d.). There are other aspects to AI, including data harmonization, natural language processing and computer vision. Currently, a fully autonomous, general AI (AGI) remains a theoretical capability but has not been convincingly demonstrated. However, the competition within the tech industry is fierce, and such an AGI could be a reality within the next decade.[8]

8 Google announced its Gemini model could reach AGI within the next decade (Knight, 2025).

Natural language processing (NLP) refers to a capability for AI to understand human language. This enables highly sophisticated translation, as well as recognition, understanding, and extraction of text-based information (Stryker and Holdsworth, 2024). This powerful function could make analysis of open-source information a less work-intensive task for those tasking with monitoring. For example, NLP-based AI can be used to monitor publications and flag potential research of concern (Liu, 2025); to review government procurement and funding documents; to monitor media for a spike in reports of symptoms associated with a potential outbreak (Carter et al., 2020);9 and to review national implementing legislation (Liu, 2025). Perhaps the simplest task to begin with could be using NLPs to translate CBM submissions and collate the data contained within to improve utilization by States Parties.

In addition to text-based analysis, AI can be trained to analyze large datasets, for example trade data, and downloads of databases or software use (Appleton et al., 2022). Digitalization of data at facilities and ML analysis could make it easier to analyze records and data collected during process control during facility inspections (Revill et al., 2022). Likewise, it could be primed to flag known sequences of concern or those which have the potential to be pathogenic; this is a feature which is already being implemented in newer technologies for detection. Computer vision can be used to recognize dual-use equipment in photographs and other visual media from facilities (Withorne, 2020).

In addition to initial flagging and analysis of information, AI can be leveraged for big data analysis which enables identification of relationships and patterns beyond the scope of human recognition. It may be possible to train an algorithm on a reference set of resources of concern flagged by human researchers (Buse et al., 2022). With regards to the methodology of this report, if AI could help refine the model of 'normal' for dual-use biotechnology and identify observables for clarification, it would significantly reduce the workload for human monitors. Others have proposed this idea of training AI to help with prioritization of facilities for inspection (Appleton et al., 2022).

However, training such algorithms is likely to be resource intensive, as it entails collation of extensive amounts of data (Appen, 2024; Withorne, 2020). Additionally, the data which is used to train algorithms is essential, thus could be targeted and/or called into question itself in order to discredit the algorithm (Kundaliya, 2025; Davies, 2024; Appleton et al., 2022).

Further, many AI algorithms (if left unconstrained) tend to be 'black boxes', meaning there is not necessarily a clear logic behind the results they yield. Sometimes this is due to finely tuned complexities that cannot be worked out retroactively, yet in other cases it could be due to arbitrary conditions induced to fit to a dataset. As one relevant example, many of the current machine learning algorithms which have been trained to predict pathogenicity from genomic data "often memorize strain-specific information rather than understanding the underlying biological mechanisms" (Wheeler, 2025). This is an active research priority in computational genetics, yet it is important for users of such algorithms to understand the extent to which they 'memorize' rather than 'understand'. To this end, existing tools for machine learning analysis are often designed for research, rather than investigation. They will be missing quality control and certification to evidentiary standards, although this could be mitigated depending on how they are used (Appleton et al., 2022).

Suitability for Capturing Observables

Table 1 indicates compliance monitoring approaches for selected observables identified in Chapter 3 that are possible following the emergence of the new technologies and techniques discussed above.

9 See for example the Global Public Health Intelligence Network (GPHIN).

Table 1: Monitoring approaches enabled by emerging technologies

	Indicator	Compliance Monitoring Approach Possible in 2025[10]
Dual-use divergences in large-scale manufacturing	High level of containment during processing, inconsistent with facilities for civilian use	Trade data indicates imports of protective equipment; government tenders for protective equipment; photos posted online by site staff show containment measures.
	Purchase of reagents (growth media, serums, buffers, etc.) not in line with standard manufacturing practices; in large quantities without a clear end use; through a rotation of multiple suppliers	Monitoring trade data, utilizing machine learning; inconsistencies between AIS data and RF imagery could indicate dark ships.
	Missing or conflicting records of operations	Machine learning tool flags records of operations inconsistent with operational data for a similar site, on which it was trained; natural language processing model flags repeating segments of text-based records.
	Mothballed but still-working equipment in pharmaceutical facilities	On-site inspection needed; likely little change since VEREX.
	Work with animal models and nonhuman primates in experimental programs, without corresponding publications on animal model studies	Shipment records of animals, electro-optical imagery or SAR indicating buildings dedicated to housing mammals, combined with satellite thermal imagery of a large heat signature from a lab equipped for mammalian testing (indicating incineration); monitoring of publications.
	Overly thorough treatment of waste streams	Hyperspectral imagery reveals traces of compounds used for decontamination; downstream sampling and MS analysis reveals compounds used for decontamination.
	Use of disposable plastic jackets and piping for fermentation vessels	Photos or videos posted of site show single-use materials for equipment; equipment tenders list single-use materials.
	General security measures not typical for civilian facilities	Electro-optical imagery reveals fencing and access control points.
Equipment & Facilities	Construction of high/maximum containment facilities	Satellite imagery of facility construction shows possible BSL3 or BSL4 building design.
	Unclear purpose or management of facilities	Lack of publicly available information, either through facility/management websites, or publications emerging from facilities.
	Defense labs funded by military budget, changes to budget allocation for biodefense	Monitoring of government budgets.
	Built by a new private company	Company registration records.
	Remote locations	Visible on satellite imagery.
	Military sites with large-scale refrigeration	Cool thermal signature at sites of interest, plus energy infrastructure necessary for large-scale refrigeration visible on satellite imagery.
	Import of equipment on AG control list	Monitoring trade data, utilizing machine learning.
Materials	Pathogenic agents or genetic material/proteins	Rapid identification with biosensors, qPCR, pathogen agnostic identification and/or confirmation with deep sequencing.

10 As a threshold of evidence, providing the basis for further clarification of compliance.

	Indicator	Compliance Monitoring Approach Possible in 2025
	Signs of collection of dangerous strains, either through field research or repositories, without corresponding research into MCMs	Monitoring of publications and conference submissions on research into MCMs; open-source reports of presence of foreign researchers in endemic or epidemic areas; records of access to strain repositories.
	Signs of genetic engineering, potentially including de novo synthesis	Monitoring of publications and conference submissions to determine capability; signatures may be identifiable with microbial forensics (full sequence, with ML-enabled analysis and comparison to reference library of known natural and modified sequences to indicate shortlist of potential sources of modification).
Expertise & Human Resources	Academic research, including sudden cessation of publications	Monitoring of publications and conference participation.
	Experts in bioprocess engineering, virologists, toxicologists, molecular biologists, epidemiologists, and/or immunologists	Monitoring of publications and publicly available data on academic institutions in-country, including courses and certifications.
	Sufficient staffing of laboratory/process technicians, with stringent clearance requirements	Submission of an application to work in a technician position at the facility (if posting is available online).
	Lack of public job postings for relevant sites	No publicly available job postings for relevant sites; not mentioned as an employer on any social media platforms used for professional networking.
	Unusual outbreaks, infection and/or death of relevant scientists, strict culture of repressing biosafety accident information	Failure to report an outbreak under the IHR; obituaries in newspapers combined with records of employment on social media platforms used for professional networking, or affiliations indicated in publications/conference registrations.
	Misuse of epidemiological dispersion models, biological simulation platforms, toxicology models, etc.	Monitoring of publications; records of access to open-source code for models.
Defense & Military	Changes to frequency and scope of CBRN exercises	Creative monitoring of open-sources (e.g. public data from a fitness tracking application indicates increased activity at a military exercise ground) or activity detected on satellite imagery; public reporting of CBRN exercises.
	Changes in military vaccination and MCMs	Monitoring of government tenders for vaccine production.
Public Sentiment & Internal Shifts	Buzz on social media and in news media about specific facilities or activities	Monitoring social media and news, augmented by text mining algorithms.
	Shifts in public opinion on biological and chemical weapons	Informatics based on open-source sentiment tracking (from data collected through text mining of social media).

Clearly, there have been significant advancements in science and technology since VEREX issued its final report. This chapter is not the first to review these changes and address them within the context of monitoring compliance with the BWC. While these informal contributions can serve as a basis for further discussion within the BWC, particularly during the WG and in any follow-on initiatives, they are not produced with a common methodology, nor at consistent intervals. They address slightly different considerations, depending on the perspectives of their authors, which may differ from those that would be

prioritized by another ad hoc group of technical experts. There are discussions in the WG on reaching a fundamental, shared basis for understanding compliance and verification. This is a reversal of the process adopted in the 1990s, when the BWC first attempted to tackle the issue of verification, yet it is unclear yet to what extent some of the technical practicalities could help to coalesce understanding of the intrusiveness and level of assurance provided by any compliance and verification approaches through the WG.

Keeping Track of Emerging Technology

This raises another fundamental issue, in addition to the chicken-and-egg version of setting political and technical parameters on verification. If granted more capacity to undertake compliance monitoring, how should the BWC keep track of relevant technology? How does it prevent another three decades from passing before it renews a technical review process?

One option is to build a body (such as the S&T board already being discussed under another WG strand) that is tasked with monitoring verification-relevant technologies in addition to providing input on emerging risks, or opportunities for international cooperation under Article X. Benefits of this setup include the ability to reconstitute a board to respond to developments in the field and make full use of cutting-edge expertise. On the other hand, the proposal to move forward on establishing such a mechanism was blocked at the previous WG; this potential mechanism may continue to be dogged by political resistance by a few States Parties in the near future. Even once that issue is bypassed, implementation is still likely to encounter issues with adequate resource allocation, based on the current state of funding for IGOs.

A more pared-back approach could be granting the ISU a more flexible mandate which allows it to experiment with applying some of the less resource-intensive emerging compliance monitoring approaches. For example, it could trial some of the proposals of using OSINT methods and natural language processing algorithms to prepare CBMs for States which have not submitted any yet and then submit them to the States for review. Or, it could entail the ISU soliciting input from civil society, such as commissioning a fully peer-reviewed report or hosting an expert workshop on compliance monitoring technologies. This product could carry more weight than independent outputs from civil society, given the involvement of the ISU, and mimics a culture at the IAEA which has fostered quite useful innovations in nuclear safeguards. Yet this option requires a bold and creative approach, while also making the ISU vulnerable to accusations of bias or a lack of rigor. Further, it would require at least a modest increase in the ISU's resourcing (one additional staff member), with more needed if any validation of equipment and techniques were undertaken. This capacity issue has plagued preparations for the UN Secretary-General's Mechanism (UNSGM) as well, the solution for which has been a heavy reliance on assistance from States, which can lead to inconsistent approaches and duplication of efforts.

The third option is to continue with an infrequent, formal convening of technical experts to review developments and make recommendations. VEREX did make some predictions of what could be available in the years following its report, but these guesses appear to have been somewhat conservative. A useful contribution in considering this approach would be to analyze what percentage of VEREX's predictions were realized, and how quickly they occurred after the report's publication. This may lend a better sense of how often these periodic meetings should take place.

It is quite easy to overemphasize the largest leaps in capability from a purely technical standpoint, but this consideration should also be balanced against utility across the full range of compliance monitoring. Approaches that prove useful for routine trust-building are likely to be used far more extensively than methods that have utility limited to on-site sampling. Perhaps efforts to implement and prepare emerging technologies should be somewhat proportionate to how often they are expected to be used. Of course, there is a deterrent function to verification; our ability to accurately attribute the origin of modification

to genetic material may reach a point wherein would-be perpetrators lose faith altogether in their ability to avoid indictment (or at least are wary enough of being identified in the future, on the basis of archived samples).

At this point, it may be more difficult to agree upon a set of technologies and techniques for compliance monitoring, given the explosion of available capabilities and the still-rapidly evolving pace of progress in the biological sciences. Any formal suite of tools would need to be validated, perhaps incrementally, and with the understanding that by the time a thorough validation process is complete, a given technology may be outdated.

Finally, while this chapter has compared the emerging technologies and techniques against their ability to address observables outlined in earlier chapters, there are other useful case studies. One would be to consider how modern approaches could have been applied by UNSCOM and UNMOVIC. Some have touched briefly on this (VERTIC and UNIDIR, 2003; Meier, 2006; Wilson and Smidovich, 2021), but there is much more detail that could be gleaned from analyzing methods disclosed in their reports and interviewing former inspectors to identify information gaps that could be filled today. Another would be to apply some of the identified methods to evaluating the evidence presented during the Article V consultations over biological laboratories in Ukraine. This is inspired by an individual technical assessment conducted by the late Raymond Zilinskas, of Cuban claims in the only previous public Article V consultation process. Following his assessment, he noted the lack of input of this sort from States Parties, the need for some standing technical capacity to evaluate the information provided during consultation and clarification, and the missed opportunity for provision of samples to parties to conduct independent analyses (Chevrier, 2020). The application of these techniques to addressing a compliance concern earlier on in the spectrum than a formal, on-site investigation is likely to confirm Zilinskas' insights, but could lead to useful considerations of the threshold of reliability of the evidence produced by various combinations of the compliance monitoring approaches discussed above, particularly when compliance will ultimately be a judgement reached by political consensus.

References

Ad Hoc Group of Governmental Experts to Identify and Examine Potential Verification Measures from a Scientific and Technical Standpoint (1993) *BWC/CONF.III/VEREX/9*. [online]. Available from: https://front.un-arm.org/wp-content/uploads/2020/12/BWC_CONF.III_VEREX_09.pdf (Accessed 20 March 2025).

Anon (n.d.) *Development and Evolution of PCR* [online]. Available from: https://www.genengnews.com/insights/development-and-evolution-of-pcr/ (Accessed 17 March 2025).

Anon (n.d.) *Home – Techbiot* [online]. Available from: https://techbiot.eu/#about (Accessed 10 March 2025).

Anon (n.d.) *Landsat Data Access | U.S. Geological Survey* [online]. Available from: https://www.usgs.gov/landsat-missions/landsat-data-access (Accessed 17 March 2025).

Anon (2024) *On a Special Conference and the ICA and S&T mechanisms*. [online]. Available from: https://docs.un.org/en/BWC/WG/5/WP.21 (Accessed 17 March 2025).

Anon (n.d.) *Project BEACON: Using OSINT methods in BWC verification – BlueDot Impact* [online]. Available from: https://biosecurityfundamentals.com/projects/project-beacon-using-osint-methods-in-bwc-verification/ (Accessed 10 March 2025).

Anon (2002) *TREATY ON OPEN SKIES*.

Appen (2024) *The State of AI in 2024: Navigating Challenges and Embracing Opportunities*.

Appleton, E. et al. (2022) *Feasibility of on-site verification*. [online]. Available from: https://static.igem.org/websites/responsibility/2022/bwc-verification/ssrn-id4213018-feasibility-of-on-site-verification.pdf (Accessed 10 March 2025).

Axe, D. (2024) Russia has expanded site of past bioweapons research, satellite images show. *The Washington Post*. 25 October. [online]. Available from: https://www.washingtonpost.com/national-security/interactive/2024/russia-biological-chemical-weapons-laboratory-expansion/ (Accessed 10 March 2025).

Axon Enterprise, Inc. (2023) *The complete history of drones for police and law enforcement* [online]. Available from: https://www.axon.com/resources/history-of-drones (Accessed 19 March 2025).

Bhalla, N. et al. (2016) Introduction to biosensors. *Essays in Biochemistry*. [Online] 60 (1), 1. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC4986445/ (Accessed 20 March 2025).

BioFire Defense (2025) *The BIOFIRE ® SPOTFIRE ® System* [online]. Available from: https://www.biofiredefense.com/products/biofire-spotfire/ (Accessed 21 March 2025).

Biosecure & IAP (2016) *The Biological and Toxin Weapons Convention: Implications of advances in science and technology*. [online]. Available from: https://royalsociety.org/-/media/policy/projects/biological-toxin-weapons-convention/biological-weapons-technical-document.pdf (Accessed 10 March 2025).

Block, L. (2023) To cite this article: Ludo Block (2024) The long history of OSINT. *Journal of Intelligence History*. [Online] 23 (2), 95–109. [online]. Available from: https://www.tandfonline.com/action/journalInformation?journalCode=rjih20 (Accessed 18 March 2025).

Bonah, E. et al. (2019) Application of Hyperspectral Imaging as a Nondestructive Technique for Foodborne Pathogen Detection and Characterization. *Foodborne Pathogens and Disease*. [Online] 16 (10), 712. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC6785170/ (Accessed 10 March 2025).

Budowle, B. et al. (2014) Validation of high throughput sequencing and microbial forensics applications. *Investigative Genetics 2014 5:1*. [Online] 5 (1), 1–18. [online]. Available from: https://investigativegenetics.biomedcentral.com/articles/10.1186/2041-2223-5-9 (Accessed 13 March 2025).

Buse, S. et al. (2022) *A Model Compliance Regime for the Biological Weapons Convention*. [online]. Available from: https://dx.doi.org/10.2139/ssrn.4430388 (Accessed 10 March 2025).

Carter, D. et al. (2020) Global public health surveillance using media reports: Redesigning GPHIN. *Studies in Health Technology and Informatics*. [Online] 270843–847. [online]. Available from: https://pubmed.ncbi.nlm.nih.gov/32570501/ (Accessed 24 June 2025).

Chevrier, M. I. (2020) Compliance mechanisms and their implementation: the contrast between the Biological and Chemical Weapons Conventions. *The Nonproliferation Review*. [Online] 27 (4–6), 475–486. [online]. Available from: https://www.tandfonline.com/doi/abs/10.1080/10736700.2020.1878666 (Accessed 13 March 2025).

Cropper, N. et al. (2022) *Creating a Verification Protocol for the Biological Weapons Convention: A MODULAR-INCREMENTAL APPROACH*. [online]. Available from: https://www.nti.org/wp-content/uploads/2022/06/Creating-a-Verification-Protocol_FINAL_June2022.pdf (Accessed 10 March 2025).

Davies, P. (2024) ChatGPT, Grok, Gemini and other AI chatbots are spewing Russian misinformation, study finds. *Euronews*. 18 June. [online]. Available from: https://www.euronews.com/next/2024/06/18/chatgpt-grok-gemini-and-other-ai-chatbots-are-spewing-russian-misinformation-study-finds (Accessed 24 June 2025).

Ferreira, L. da C. et al. (2024) Hyperspectral imaging for the detection of plant pathogens in seeds: recent developments and challenges. *Frontiers in Plant Science*. [Online] 151387925.

Fradkov, A. (2020) Early History of Machine Learning. *IFAC PapersOnLine*. 53 (2), 1385–1390. [online]. Available from: https://pdf.sciencedirectassets.com/313346/1-s2.0-S2405896321X0002X/1-s2.0-S2405896320325027/main.pdf (Accessed 22 May 2025).

Franco-Duarte, R. et al. (2019) Advances in Chemical and Biological Methods to Identify Microorganisms—From Past to Present. *Microorganisms*. [Online] 7 (5), 130. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC6560418/ (Accessed 20 March 2025).

Goldman, D. & Domschke, K. (2014) *Making sense of deep sequencing*. [Online] [online]. Available from: https://academic.oup.com/ijnp/article/17/10/1717/2357198 (Accessed 19 March 2025).

Hanham, M. (2020) *Emerging Trends in Commercial Remote Sensing for Nuclear Arms Control*. [online]. Available from: https://unidir.org/wp-content/uploads/2023/05/Science-and-Technology-for-Monitoring-and-Investigation-of-WMD-Compliance.pdf (Accessed 17 March 2025).

Haulman, D. (2003) *U.S. Unmanned Aerial Vehicles in Combat, 1991-2003*. [online]. Available from: https://www.dafhistory.af.mil/Portals/16/documents/Studies/AFD-070912-042.pdf (Accessed 19 March 2025).

Higgs, M. (2024) *The Latest Developments in Sequencing Technologies* [online]. Available from: https://frontlinegenomics.com/the-latest-developments-in-sequencing-technologies/ (Accessed 10 March 2025).

ICEYE (2025) *Accurate, near real-time Earth monitoring with SAR data*. [online]. Available from: https://www.iceye.com/hubfs/Downloadables/SAR_Data_Brochure_ICEYE.pdf (Accessed 17 March 2025).

International Organization for Standardization (n.d.) *What is artificial intelligence (AI)?* [online]. Available from: https://www.iso.org/artificial-intelligence/what-is-ai (Accessed 22 May 2025).

Kimball, D. (2024) *The Biological Weapons Convention (BWC) At A Glance* [online]. Available from: https://www.armscontrol.org/factsheets/biological-weapons-convention-bwc-glance-0 (Accessed 21 March 2025).

Knight, W. (2025) Google's AI Boss Says Gemini's New Abilities Point the Way to AGI. WIRED [online]. Available from: https://www.wired.com/story/googles-ai-boss-says-geminis-new-abilities-point-the-way-to-agi/ (Accessed 22 May 2025).

Kundaliya, D. (2025) *OpenAI shutters ChatGPT accounts used by Russian, Chinese, Iranian hacker groups* [online]. Available from: https://www.computing.co.uk/news/2025/security/openai-shutters-hacker-chatgpt-accounts (Accessed 24 June 2025).

Li, C. N. & Nakamura, M. M. (2022) Utility of Broad-Range PCR Sequencing for Infectious Diseases Clinical Decision Making: a Pediatric Center Experience. *Journal of Clinical Microbiology*. [Online] 60 (5), e02437-21. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC9116169/ (Accessed 21 March 2025).

Liu, N. (2022) *Everything you ever wanted to know about SAR satellite data and the ecosystem but were afraid to ask* [online]. Available from: https://geoawesome.com/eo-hub/everything-you-ever-wanted-to-know-about-sar-satellite-data-and-the-ecosystem-but-were-afraid-to-ask/ (Accessed 17 March 2025).

Liu, Y. (2025) Discovering topics and trends in biosecurity law research: A machine learning approach. *One Health*. [Online] 20100964.

Lu, B. et al. (2020) Recent Advances of Hyperspectral Imaging Technology and Applications in Agriculture. *Remote Sensing*. [Online] 12 (2659). [online]. Available from: www.mdpi.com/journal/remotesensing (Accessed 18 March 2025).

Meier, O. (2006) *Aerial Surveillance and BWC Compliance Monitoring*.

NASA (n.d.) *Landsat 9 Bands* [online]. Available from: https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-bands/ (Accessed 17 March 2025a).

NASA (n.d.) *RADARSAT-1* [online]. Available from: https://www.earthdata.nasa.gov/data/platforms/space-based-platforms/radarsat-1 (Accessed 17 March 2025b).

National Human Genome Research Institute (2024) *Human Genome Project Fact Sheet* [online]. Available from: https://www.genome.gov/about-genomics/educational-resources/fact-sheets/human-genome-project (Accessed 21 March 2025).

Park, S. & Puccioni, A. (2024) *North Korea's Pursuit of an ELWR: Potential Power in Nuclear Ambitions?* [online]. Available from: https://www.38north.org/2024/01/north-koreas-pursuit-of-an-elwr-potential-power-in-nuclear-ambitions/ (Accessed 20 March 2025).

Planet Labs (n.d.) *Detect, Monitor, and Minimize Risk Across Large Geographic Areas* [online]. Available from: https://www.planet.com/solutions/broad-area-management/ (Accessed 17 March 2025).

Revill, J. (n.d.) *Compliance Revisited: An Incremental Approach to Compliance in the Biological and Toxin Weapons Convention*. [online]. Available from: www.miis.edu (Accessed 10 March 2025).

Revill, J. et al. (2022) *WMD COMPLIANCE ENFORCEMENT SERIES BACK TO THE FUTURE FOR VERIFICATION IN THE BIOLOGICAL DISARMAMENT REGIME?* [online]. Available from: www.unidir.org| (Accessed 10 March 2025).

SatVu (2025) *SatVu's HotSat-1 Archive Available to U.S. Government Agencies Through the Global Data Marketplace* [online]. Available from: https://www.satellitevu.com/news/satvus-hotsat-1-archive-available-to-u-s-government-agencies-through-the-global-data-marketplace (Accessed 17 March 2025).

SatVu (2023) *World first in high resolution satellite thermal imaging defines new era of climate monitoring* [online]. Available from: https://www.satellitevu.com/news/world-first-in-high-resolution-satellite-thermal-imaging-defines-new-era-of-climate-monitoring (Accessed 17 March 2025).

Schmedes, S. & Budowle, B. (2019) Microbial Forensics. *Encyclopedia of Microbiology*. [Online] 134. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC7149751/ (Accessed 10 March 2025).

Singhal, N. et al. (2015) MALDI-TOF mass spectrometry: an emerging technology for microbial identification and diagnosis. *Frontiers in Microbiology*. [Online] 6 (AUG), 791. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC4525378/ (Accessed 20 March 2025).

Stringham, C. et al. (2024) *Full-resolution SLC Imagery: Revolutionizing Commercial SAR Data* [online]. Available from: https://www.capellaspace.com/blog/full-resolution-slc-imagery-revolutionizing-commercial-sar-data (Accessed 17 March 2025).

Stryker, C. & Holdsworth, J. (2024) *What Is NLP (Natural Language Processing)?* [online]. Available from: https://www.ibm.com/think/topics/natural-language-processing (Accessed 24 June 2025).

Suresh, N. (n.d.) *Final Report for the Tabletop Exercise* [online]. Available from: https://luxurious-quokka-033.notion.site/Final-Report-for-the-Tabletop-Exercise-af639d909c16475e90f0d49727397e09 (Accessed 18 March 2025).

ThermoFisher Scientific (n.d.) *Overview of Mass Spectrometry* [online]. Available from: https://www.thermofisher.com/uk/en/home/life-science/protein-biology/protein-biology-learning-center/protein-biology-resource-library/pierce-protein-methods/overview-mass-spectrometry.html (Accessed 20 March 2025a).

ThermoFisher Scientific (n.d.) *The History of PCR* [online]. Available from: https://www.thermofisher.com/uk/en/home/brands/thermo-scientific/molecular-biology/molecular-biology-learning-center/molecular-biology-resource-library/spotlight-articles/history-pcr.html (Accessed 17 March 2025b).

Thompson, J. F. & Milos, P. M. (2011) The properties and applications of single-molecule DNA sequencing. *Genome Biology*. [Online] 12 (2), 1–10. [online]. Available from: https://genomebiology.biomedcentral.com/articles/10.1186/gb-2011-12-2-217 (Accessed 12 March 2025).

treangenlab (2021) *PlasmidHawk* [online]. Available from: https://gitlab.com/treangenlab/plasmidhawk (Accessed 20 March 2025).

Turgeon, T. (2024) *Radio Frequency Collection: Securing the Maritime Domain* [online]. Available from: https://www.darkshipping.com/post/securing-the-maritime-domain-with-rf-data (Accessed 20 March 2025).

Tytgat, O. (2022) *Bringing Science to the Scene: Novel strategies for portable DNA profiling*. Ghent, Belgium: Ghent University. [online]. Available from: https://www.researchgate.net/profile/Olivier-Tytgat/publication/362991666_Bringing_Science_to_the_Scene_Novel_strategies_for_portable_DNA_profiling/links/630bf70dacd814437fe479ea/Bringing-Science-to-the-Scene-Novel-strategies-for-portable-DNA-profiling.pdf (Accessed 10 March 2025).

VERTIC & UNIDIR (2003) *Coming to Terms with Security: A Handbook on Verification and Compliance*. [online]. Available from: https://www.vertic.org/media/assets/Handbook.pdf (Accessed 10 March 2025).

Walker, J. R. (2020) Reflections on the 2001 BWC Protocol and the verification challenge. *The Nonproliferation Review*. [Online] 27 (4–6), 507–515. [online]. Available from: https://www.tandfonline.com/doi/abs/10.1080/10736700.2020.1865635 (Accessed 13 March 2025).

Wang, Q. et al. (2021) PlasmidHawk improves lab of origin prediction of engineered plasmids using sequence alignment. *Nature Communications 2021 12:1*. [Online] 12 (1), 1–12. [online]. Available from: https://www.nature.com/articles/s41467-021-21180-w (Accessed 20 March 2025).

Wheeler, N. (2025) *AMR and Emerging Biotechnologies*. [online]. Available from: https://doi.org/10.71706/6623f95c-4a10-49b4-afd2-a708792d5e10 (Accessed 21 March 2025).

Wilson, H. & Smidovich, N. (2021) Perspectives on UNSCOM and UNMOVIC: An interview with Nikita Smidovich. *Bulletin of the Atomic Scientists*. [Online] 77 (4), 184–187. [online]. Available from: https://www.tandfonline.com/doi/abs/10.1080/00963402.2021.1941564 (Accessed 13 March 2025).

Wilton Park (2022) *Emerging technologies and the Nuclear Non-Proliferation Treaty In partnership with the Stanley Center for Peace and Security, and King's College London with support from the MacArthur Foundation*. [Online]. Available from: https://www.wiltonpark.org.uk/event/emerging-technologies-and-the-nuclear-nonproliferation-treaty/. (Accessed 10 March 2025).

Withorne, J. (2020) *Machine Learning Applications in Nonproliferation: Assessing Algorithmic Tools for Strengthening Strategic Trade Controls*. [online]. Available from: www.nonproliferation.org/dc (Accessed 10 March 2025).

Wurtz, N. et al. (2023) Simple Wastewater Preparation Protocol Applied to Monitor the Emergence of the Omicron 21L/BA.2 Variant by Genome Sequencing. *Viruses*. [Online] 15 (2), 268. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC9965846/ (Accessed 17 March 2025).

Yang, S. & Rothman, R. E. (2004) PCR-based diagnostics for infectious diseases: uses, limitations, and future applications in acute-care settings. *The Lancet. Infectious Diseases*. [Online] 4 (6), 337. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC7106425/ (Accessed 21 March 2025).

Chapter 7

Conclusions and Recommendations

This report's objective is to highlight the observable elements and capabilities that a compliance monitoring regime could focus on, in order to develop a framework to evaluate the efficacy of different proposed monitoring approaches.

While CBMs were adopted by consensus as an interim step to increase transparency and confidence, they were never intended for verification or compliance assessment. However, they do provide an example of a specified scope for monitoring that can be evaluated for its ability to build a country-specific baseline of normal capabilities – contingent, of course, on the data being complete, accurate and regular. Across the scenarios, 25–50% of the identified observables were captured or partially captured by the CBMs. Observables most likely to be missed include dual-use divergences in manufacturing, certain materials, and specific defense-related indicators – highlighting areas States Parties could consider for updated CBM forms or supplementary efforts. CBMs have more verification utility than often recognized; however, this utility relies on trust in complete and correct submissions.

VEREX identified a broad set of verification measures that remain relevant today. The experience of the Ad Hoc Group underlined how getting the details right can be difficult. VEREX categories remain broad: while, for example, declarations were assessed as a measure, specific declarations and the requirements of any specific declaration, were not within the mandate of VEREX. Thirty years on, the VEREX categories are broad enough to capture wide ranges of interpretations on their implementation. Emerging technologies fit within VEREX's original categories but expand capability.

Scientific advances both increase pathways for biological weapons development and enhance monitoring capabilities, including by shifting what may once have been on-site monitoring measures to off-site and increasing analytical capacity.

Reflections on scope

This report presented a set of scenarios which were used to develop a list of observables of non-compliance with the BWC. Necessarily, the use of scenarios entailed some restriction on the scope of possible threats and proliferation pathways. Further work may look at different scenarios, using the same methodology, to possibly identify other observables. Other scenarios may include different approaches to developing biological weapons, as well as different choices of targets, agents, and weaponization routes. While this project focused on state actors due to the focus on the BWC as an international agreement, future work may also include scenarios where non-state actors seek to acquire biological weapons.

While the project team noted that many of the observables are, individually, related to dual-use capabilities that have civilian applications, it should also be noted that the scenarios considered in this report all featured production of biological weapons. A different application of this project's methodology, expanding and adding detail to the analysis of the possible impact and applicability of different monitoring measures, could also be used to consider how more ambiguous scenarios could be clarified and distinguished from proliferation. For example, it could consider activities for biodefense purposes which

fall into a grey zone of compliance as assessed by other states, disinformation or lawfare-based antagonism towards the convention itself, and failure to implement positive obligations such as national implementation or international cooperation and assistance. Some possible approaches to addressing these compliance concerns were addressed in the Emerging Technologies chapter, yet more work could show how different approaches can be used to clarify these kinds of ambiguities.

Compliance monitoring should also capture behavioral indicators of responsible engagement, transparency, and norm adherence,[1] complementing technical observables. These behavioral markers strengthen confidence and reinforce the normative fabric of the BWC.

Finally, the authors wish to note that there are other ways of being in non-compliance with the convention, including by failing to comply with obligations set out under Articles II-IV. These have historically been overlooked, with the focus of verification discussions being on Article I; this report has also reinforced this focus, but it is worth emphasizing that consideration of compliance should not end here.

The spectrum of compliance monitoring

It is useful to view compliance monitoring as a spectrum of different options, ranging from transparency and voluntary measures to more intensive processes, such as on-site investigations and challenge inspections. Generalizing, one can say that moving along this spectrum of effectiveness – in terms of greater capacity to detect possible non-compliance and overall level of confidence – comes at the cost of political and practical intrusiveness, disruption, and resource requirements. This is overall a reasonable argument, and one well known in the BWC community; however, it is worth expanding it a bit and noting a few caveats about it.

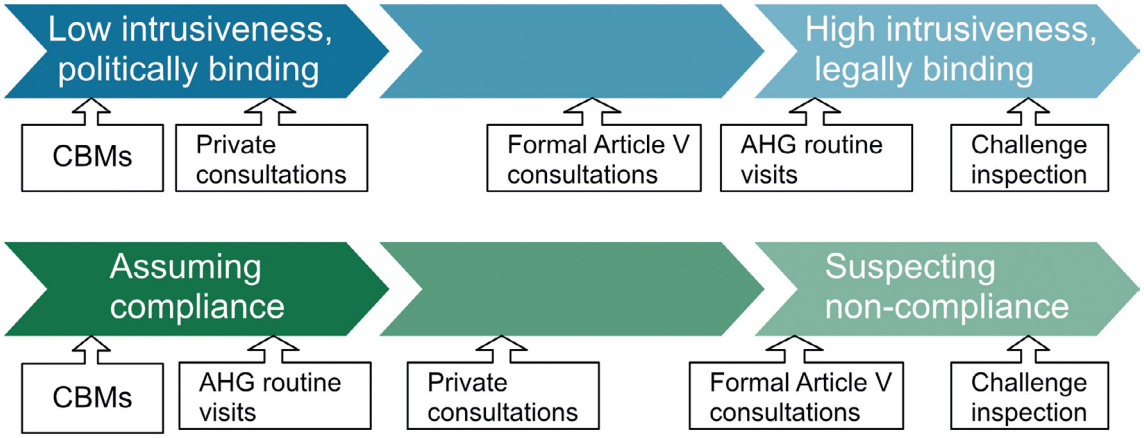
The first caveat to note is that while the measures at the 'lightest' end of the verification spectrum are mostly voluntary, and many at the highest end of the spectrum tend to be formal, legally binding processes, this should not be read to mean that all legally binding processes are necessarily highly intrusive and disruptive. Some processes, like treaty-mandated national declarations, would still be relatively unintrusive; conversely, states could engage in voluntary transparency measures that are quite intrusive, such as inviting others for voluntary site visits and peer review.

The second caveat is that the level of effectiveness and the level of intrusiveness of verification measures are not always directly proportional. There are measures and approaches, for example some of the ones described in Chapter 6, that can provide significant information and a solid level of confidence in findings without the need for on-site activity; this is the case for example of remote monitoring options empowered by recent technologies, whether they be satellite imagery analysis, or AI-powered monitoring of research and publications. In some cases, relatively un-intrusive measures could be able to monitor only certain observables but prove very effective at covering those – reinforcing the overall finding of VEREX that the key to a BWC verification regime is likely to be the judicious layering and combination of different approaches. One important aspect of this, going forward, might include the ability to adjust the combination of approaches in response to the situation, for example activating more intrusive and in-depth measures when relevant anomalies or ambiguities are identified.

This last point raises a final caveat, which is that the concept of "intrusiveness" itself may need to be revisited. Traditionally, measures are understood as intrusive when they entail on-site activity, with states objecting to the disruption of operations at facilities caused by inspections, as well as the risk to either national security information, or commercially sensitive data. However, it is worth noting that there may well be options for on-site measures designed to greatly reduce intrusiveness and disruption; and

1 See Kelle and Dando, 2025.

Figure 2: Overlapping spectrums of trust and the appropriate level of intrusiveness.



at the same time, that some remote monitoring measures – usually seen as fairly unintrusive – have grown capable enough that the sheer ability to collect information may raise objections. Finally, a related but separate point is that of cost: while in-person, on-site activities are routinely understood to be very expensive, and that largely remains the case, the resource requirements of remote activities need to be also taken into account. For example, analysis of data and satellite imagery in large quantities requires a large staff of trained analysts; and training AI models, itself, requires significant amounts of data, energy, and work.

Overall, while a general spectrum of intrusiveness and effectiveness is useful, individual measures can and should be evaluated on their own terms; and very often, on the merits of the specific implementation proposed (this is a key reason why it is difficult to provide high-level evaluations for the measures identified in VEREX, as discussed in Chapter 5). Ultimately, what combination of monitoring measures is deemed sufficient depends on the level of confidence required by the States Parties. This, in turn, is likely to depend on the specific context, and points to another spectrum that needs to be discussed, that of trust and concern. While 'trust' has multiple possible definitions in arms control and international affairs, it is useful to see the spectrum as whether States Parties are approaching each other with the assumption of compliance or the suspicion of non-compliance. Figure 2, below, shows the two spectrums – that of intrusiveness and that of trust and concern, side by side; taken together, one can observe how they can proceed in parallel. The most immediate conclusion is that as concerns rise, and the political context moves to one of suspicion of non-compliance, so the verification spectrum moves to more intrusive and in-depth measures.

Plans for monitoring under the BWC should consider what measures would be appropriate at all levels of trust, including situations of high confidence and low suspicions, and how processes may escalate when and if significant concerns come to light. This is not, it should be noted, a call to introduce a highly formalized system that is active at all times: indeed, States Parties may decide that CBMs (perhaps expanded) and other voluntary measures are adequate for 'business as usual', and more formal processes – and intrusive measures – should only be reserved for moments where specific suspicions have arisen.

Advancing the debate on BWC Verification

States Parties should seek to come to a common understanding of what level of confidence in detection of non-compliance is required in different conditions. Political feasibility will drive the pace and scope for implementation of compliance monitoring, but incremental, cooperative measures can enhance transparency, build trust, and prepare the ground for more formal verification mechanisms. This could be done by building from politically feasible steps (e.g. enhanced CBMs or legally binding declarations, voluntary site visits) to more intrusive measures. Verification exercises will play a key role in determining realistic approaches, and proliferation scenarios can continue to refine monitoring priorities.

Consultation and clarification processes, if used more often and in a less confrontational manner under Article V, could shift farther away from suspicion of non-compliance on the level of trust spectrum. Public consultations under Article V have only taken place twice in the history of the BWC (Chalmers and Wingo, 2024). Thus, current perceptions of Article V are of a fundamentally escalatory procedure given the history of its use and the pathway to escalation to the UNSC through Article VI. The public nature of the process has also led to silence and lack of engagement from a large portion of States Parties who may find their diplomatic priorities conflicting with determination of compliance (Littlewood & Lentzos, 2022). However, Article V does not specify the use of multilateral consultative meetings, which were introduced by the Second Review Conference in 1986 (Revill, 2022). Consultation and clarification are most effective for actually resolving compliance concerns when conducted privately.

The more a compliance monitoring mechanism leans towards an all-or-nothing approach (lacking routine activities and only coming into effect in case of suspicious observables), the more likely it is that consultations would be the only hinge point for assessment of compliance. Routine activities or information exchanges give States Parties something to discuss that is less contentious. The Second Review Conference also provided scope for the "assistance of technical experts" to further clarify "any matter considered ambiguous or unresolved" (*Final Document of the Second Review Conference of the Parties to the BWC, 1986*). States can rely on existing mandates to practice their ability to independently assess technical evidence presented during lower-level monitoring for trust building and to de-politicize and normalize consultations undertaken to resolve ambiguities over less contentious situations.

The underlying issue of enforcement further complicates compliance issues. Not only is the determination of compliance ultimately a political decision, but given that States Parties are sovereign, enforcement is an issue of collective action. For this issue, we can draw on the policy wisdom that "collective action problems require collective responses", which can be summed up as the following: voluntary coordination, social norms and moralization, technological solutions, and laws and rules (Haidt, 2024). In the BWC context, voluntary coordination could look like Member States independently forming like-minded groups to monitor compliance, either by providing support to the BWC itself, or by information-sharing and national technical means. The widespread norm against biological weapons continues to be strong; States Parties and civil society need to continuously reaffirm and strengthen it, with the ultimate goal of discouraging biological weapons programs due to the loss of international status that would be a consequence of detection. While BWC verification is not subject to technological determinism, the availability of technologies for verification is certainly an important factor; for example, microbial forensics might reach a point where identification of modification and origin becomes so reliable and accurate that it disincentivizes the modification of pathogens to create a biological weapon. Finally, the laws and rules element is where legally binding measures come in. For the BWC, and international law more broadly, having a legally binding mechanism does not solve the issue of enforcement, but it does provide a stronger basis for internationally coordinated consequences.

Moving forward from VEREX

VEREX remains a relevant starting point, and its categories still frame most modern verification options. Integrating emerging technologies into its established frameworks offers a useful pathway forward. The proposed S&T mechanism could be granted a mandate to assess verification-relevant technology, or a new ad-hoc group could be convened specifically for this purpose. States Parties could also consider something quite radical: commissioning research to update the original VEREX report and integrate it with more recent scientific and technological developments. It is likely this could be completed on a shorter time frame and at less cost than if States Parties repeated the work themselves.

Along the spectrum of intrusiveness, emerging technologies differ in relevance. Many of the broader conclusions drawn by VEREX as to the focus of off-site and on-site monitoring still hold, although the possibilities of the amount of information collected and through what means have changed. For off-site

activities, which focus on information monitoring, novel approaches such as OSINT can help to democratize the process and can provide a large amount of context with a low level of intrusiveness (unless, as noted above, their effectiveness becomes such that states start framing them as intrusive methods). While technologies and techniques such as sequencing and microbial forensics might enable attribution to a standard which holds up in court, something which was completely infeasible in the mid-1990s, they still rely on access to physical material itself. Some of this could potentially be obtained from perimeter monitoring, but in the near future could only provide circumstantial evidence, at least until microbial forensics attain a level of validation and assurance of correct attribution that is far above what has been achieved thus far.

It may be valuable to reframe discussions away from a binary verification / no verification debate and shift to what types of information are required to assure other States Parties of compliance with the BWC: that information will differ depending on the scope and scale of biological activities within a state, its national implementation measures and the relationship between States Parties. This approach may, and likely will, lead to different requirements for different states, as those with greater capabilities may need to provide more information to demonstrate that their activities are peaceful. This has the potential to prove controversial, as states are likely to insist on being treated equally under the convention. However, there is precedent to demonstrate how the matter could be approached fairly and equitably. For example, the IAEA Safeguards regime – a highly formal verification system with multiple legal requirements and intrusive on-site inspection activities – includes a Small Quantities Protocol, an additional instrument available to countries with very little or no nuclear material, which suspends several of the more onerous obligations for these states, on the basis that the risk they pose is very low. The Small Quantities Protocol, it should be noted, contains clauses that would automatically rescind it should a state exceed a certain threshold of nuclear activities, bringing the full suite of Safeguards obligations back in force.

Monitoring by States, and beyond

At some point, civil society will begin to use the tools available to them to monitor dual-use activities by BWC States Parties. Examples of this are evident already and have emerged from the surge in open-source intelligence practitioners and audiences. These include a Washington Post article which highlighted construction and expansion at a facility associated with the former Soviet bioweapons program and an analysis of the capacity shown by the DPRK during a televised tour of a laboratory used for biopesticide research (Axe, 2024; Hanham, 2015). Many of these pieces draw on expertise developed by civil society monitoring of nuclear weapons programs; the nuclear open-source community is much better established, but it also has to deal with less ambiguity. For example, when a State conducts and operates a plutonium-producing reactor without Safeguards arrangements in place, it is fairly hard to misinterpret this activity. A notable lesson that can be learned from efforts in the nuclear field is that organizational and behavioral indicators – patterns in training, personnel networks, or institutional behavior – need to be considered alongside technical factor in a compliance assessments; both institutions and civil society have been effective in analyzing these, often through open source methods.

States Parties and independent experts tend to have slightly different ideas of the proper role for civil society, with the former seeing an opening for civil society to provide education and outreach support, and the latter seeing a more direct role in monitoring (Shearer et al., 2022). There are many instances in which an attentive civil society may pick up on certain observables or patterns yet be limited by its ability to engage with the observed state to assess its intent. There is still value in the publicization of concerns by civil society, but it is possible in some cases that States Parties may have already addressed concerns privately amongst themselves; in such cases, adding public pressure can complicate already delicate diplomatic processes.

However, it is advisable to incorporate civil society into compliance monitoring, especially given the BWC's resource constraints. For example, Raymond Zilinskas performed a *post facto* assessment of Cuban claims

during the 1997 public Article V consultations which could have greatly contributed to the consultation process; as the consultations lacked independent assessment, very few States provided their technical interpretations of the evidence, and most national statements provided support for the US or Cuban side on a seemingly purely political basis. A decade earlier, consultations had taken place between the US and the Soviet Union over the outbreak of anthrax at Sverdlovsk, but these were private and bilateral (Revill, 2022). It was not until years later that a group of scientists published their independent conclusion that the outbreak had been caused by the accidental release of aerosolized anthrax (Meselson et. al., 1994). The more recent round of consultations between the US, Ukraine and Russia could also have benefitted from independent, technical review as an official input to the process.

Recommendations

For this methodology

This report covered a number of areas of interest for the BWC and outlined a methodology that can be expanded on in the future. Next steps could include:

- **Exploring additional scenarios:** The report explored 4 scenarios (2 of which had significant commonalities), based on interests and risks recently highlighted in expert debates. Future work could expand the scope by developing additional scenarios, covering from specific technological pathways, different availability of expertise and resources, and even pursuit of biological weapons by non-state actors. All these could highlight other sets of observables.
- **Expanding analysis of organizational observables:** as noted above, patterns of training, funding, research networks and organizational indications being equally revealing as physical observables for the analysis of different scenarios. Future studies could expand this section of the observables, perhaps by studying and drawing lessons from known biological weapons programs of the past, both state- and non-state-driven.
- **Considering other verification measures:** The report started with some of the pillars of the debate of BWC verification, namely CBMs and VEREX, and added a number of emerging and novel technologies of relevance. Future work could expand to include other verification measures, such as additional technologies, or inspection techniques used in different regimes (learning from the nuclear and chemical non-proliferation regimes, for example, or from the work done under the United Nations Secretary-General Mechanism). Future work could also examine the applicability of verification measures in greater depth, for example by breaking down broad categories (such as the VEREX categories) in specific proposed applications and evaluating them. In some cases, this analysis would require a level of detail such that TTXs, expert input techniques, or even field tests, may be needed for each proposed measure.
- **Testing entire verification systems:** This report discussed verification measures individually, and noted the importance of layering different measures, but deliberately did not provide the blueprint for one complete, integrated BWC compliance monitoring regime. In the future, experts could assemble a regime out of multiple proposed measures, and "test" it by looking at how those measures, together, would cover a scenario's observables. Again, this type of analysis would probably require a TTX or similar activity, with participants who have field experience of verification.

For BWC States Parties

This report deliberately chose not to propose a single verification regime as the right choice for the BWC – instead, it sought to highlight how States Parties could continue discussions on BWC compliance monitoring in a way that is detailed, practical, and technically informed. The following are some recommendations for ways the BWC States Parties could do so:

- **Supporting the CBM process:** States should support the CBM process by submitting their CBMs regularly and with as much detail as they can. They could also trial, on a voluntary basis, processes where they present their submissions and possibly answer questions by other States Parties. Finally, while an expansion or review of the CBMs themselves may seem difficult in the current environment, states should consider expanding them, especially to plug existing gaps and improve coverage of modern technologies and research techniques.
- **Practicing and normalizing consultation and clarification:** Consultation and clarification are key to resolving anomalies and ambiguities under any verification regime, BWC included. As noted above, there have been cases of both bilateral, confidential consultations, and public processes under Article V. At present, states may see Article V as a hostile and escalatory process, given its historical use in public proceedings. BWC States Parties should consider engaging proactively and publicly in consultation and clarification, normalizing it in the BWC context and turning them from crisis mechanisms into routine confidence-building tools. This could happen through Article V, by voluntarily conducting public consultations, or disclosing that private consultations have taken place (even without needing to disclose their contents and outcomes). Voluntary discussions of CBM submissions could also be an interesting way to develop this kind of debate in the BWC context.
- **Seeking greater understanding of confidence and uncertainties in verification:** As noted multiple times during this report, the key question guiding the design of a verification regime is what level of confidence is required, and about which activities. BWC States Parties should consider and address this question, both domestically and in international fora. It is likely that states will approach the matter with different expectations and risk perception and bridging that gap is crucial in order to make progress towards BWC verification. These debates should also recognize that monitoring may have a role in different circumstances: for example, delineating where routine compliance monitoring should cross over into resolution of compliance concerns or formal verification activities, and what measures would be appropriate for the different stages.
- **Discussing the practical aspects of different verification measures:** States should engage in full with the possible uses, advantages, and challenges posed by different proposed monitoring measures. This will require a willingness to share information, especially from those states that have highly advanced expertise, and to hold technical debates in an appropriate forum. Proposed fora such as a S&T Review Mechanism or an Open-Ended Working Group on verification would offer an ideal venue for such discussion; but in their absence, states could take the initiative and foster dialogue on specific topics. This could happen via consultations, side events, or workshops convened intersessionally; it would be particularly interesting to identify a specific set of tools and convene appropriate experts to review and demonstrate their possible use. This could be effective especially for remote monitoring tools, or for new technologies such as AI.
- **Practicing verification in the field via exercises:** the Rolling Text by the Chairperson of the Working Group on the Strengthening of the Convention "encourages States Parties, on a voluntary basis, to organize and/or take part in the trial/practice application of compliance and verification measures in close cooperation with the relevant industries" (BWC/WG/6/CRP.1). Stress-testing verification measures before they become legally binding is absolutely essential. It helps to ensure their effectiveness and to prime States Parties and industries that would be affected for verification measures before they commit to them. This is a slower, yet pragmatic, approach. Additionally, the experience developed by an older generation of experts who took part in such exercises in the 1990s, the last time verification was seriously considered for the BWC, is not always easily transmitted to incoming generations of experts without the hands-on experience of seeing what does and does not work for verification in practice.

Ultimately, the effectiveness of any verification regime will rest on political cooperation and sustained normative commitment; technology and legal frameworks can enable it, but they cannot replace it.

References

Anon (1986) Final Document of the Second Review Conference of the Parties to the BWC. [online]. Available from: https://docs-library.unoda.org/Biological_Weapons_Convention_-_Second_Review_Conference_(1986)/BWC_CONF.II_13.pdf (Accessed 12 September 2025).

Axe, D. (2024) Russia has expanded site of past bioweapons research, satellite images show. *The Washington Post*. 25 October. [online]. Available from: https://www.washingtonpost.com/national-security/interactive/2024/russia-biological-chemical-weapons-laboratory-expansion/ (Accessed 10 March 2025).

Chalmers, H. & Wingo, H. (2024) *Enforcing the Comprehensive Nuclear-Test-Ban Treaty: The Role of Consultation and Clarification*. [online]. Available from: www.opennuclear.orgwww.vertic.org (Accessed 12 September 2025).

Hanham, M. (2015) *Kim Jong Un Tours Pesticide Facility Capable of Producing Biological Weapons* [online]. Available from: https://www.38north.org/2015/07/mhanham070915/ (Accessed 12 September 2025).

Haidt, J. (2024) *The Anxious Generation: How the Great Rewiring of Childhood Is Causing an Epidemic of Mental Illness*. Penguin. [online]. Available from: https://www.amazon.co.uk/Anxious-Generation-Rewiring-Childhood-Epidemic-ebook/dp/B0CGWS3JQ6 (Accessed 6 October 2025).

Kelle, A. & Dando, M. R. (2025) Behavioral arms control in the century of biology. *The Nonproliferation Review*. [Online] 1–21. [online]. Available from: https://www.tandfonline.com/doi/pdf/10.1080/10736700.2025.2505828 (Accessed 9 September 2025).

Littlewood, J. & Lentzos, F. (2022) *Russia's alleged bioweapons claims have few supporters* [online]. Available from: https://thebulletin.org/2022/10/russias-alleged-bioweapons-claims-have-few-supporters/ (Accessed 17 September 2025).

Meselson M, Guillemin J, Hugh-Jones M, Langmuir A, Popova I, Shelokov A, Yampolskaya O. (1994) The Sverdlovsk anthrax outbreak of 1979. *Science*. Nov 18;266(5188):1202-8. doi: 10.1126/science.7973702. PMID: 7973702.

Revill, J. (2022) *The Past, Present and Future of BWC Article V Consultations → UNIDIR* [online]. Available from: https://unidir.org/the-past-present-and-future-of-bwc-article-v-consultations/ (Accessed 12 September 2025).

Shearer, M. P. et al. (2022) BWC assurance: increasing certainty in BWC compliance. *Nonproliferation Review*. [Online] 29 (1–3), 47–75. [online]. Available from: /doi/pdf/10.1080/10736700.2023.2178099?download=true (Accessed 12 September 2025).

Annex I

Scenario planning and development

In order for the scenarios to support the analytical work intended for this project, they needed to be both comprehensive, in providing enough detail to develop an acquisition path, and consistent, in ensuring that different scenarios all respond to the same fundamental questions about the scope and scale of a biological weapons programme. To ensure this, the team created a framework to develop scenarios. The same framework could be used to develop other scenarios in the future, for this or similar projects.

The framework is broken down in three iterative stages, each adding further detail to the scenario consistent with the characteristics established in the previous stage. In some cases, the framework offers options to pick from; in others it requires to fill in a blank.

Scenario development framework

Stage 1: General scope and goals

- Nature and goal of the perpetrators
  - Motivation for use of biological weapons over conventional weapons
- Nature of targets
  - Human population
    - Individual
    - Non-state
    - State
  - Zoonotic
  - Crops
- Scale of program[1]
  - Single attack
  - Small-scale
  - Mass production
- Selection of Agent/agents
  - Acquisition of agent (isolation from natural source, modification of existing strain, *de novo* synthesis, etc.)

Stage 2: Infrastructure and technology

- Scale of production infrastructure
  - Laboratory scale

1 See Kaszeta, D. (2021) Small-Scale Chemical and Biological Production: Current Threats and Future Trajectories. Royal United Services Institute [online]. Available from: https://www.rusi.org/explore-our-research/publications/occasional-papers/small-scale-chemical-and-biological-production-current-threats-and-future-trajectories (Accessed 6 October 2025).

- Pilot scale
- Manufacturing scale

- Sophistication
  - Level of program advancement: reliability, organization, stability.
    - Structured processes, QA/QC, testing, training/knowledge retention.
      - This is not about access to cutting edge technology, but more about maturity and organization of the program: established processes, ability to achieve reliable/consistent results.
- Technological level
  - Conventional technologies
  - Cutting edge and emerging technologies
    - Include only Technology Readiness Level (TRL) 5 or greater: technology which has [at least] been validated in a relevant environment
    - Classify risk (and thus merit of inclusion) based on modified version of O'Brien and Nelson (2020) matrix
- Technologies and facilities for culturing, scaling up, stabilizing, stockpiling
  - Is there a goal to establish and maintain a stockpile?
    - Potential steps for upstream processing: inoculation, microbial fermentation/cell culture, harvesting, sterilization of equipment
    - Potential steps for downstream processing: Extraction/separation, purification, suspension/stabilization, analysis, integration with delivery system, sterilization of equipment
    - Do we assume batch production only (no continuous)? Stockpiling or just-in-time process design? Stockpiling stabilized agent or maintenance of a lab culture?
- Delivery Methods
  - Infection method: Aerosolized (inhalation)? Transdermal (injection or absorption)? Contamination (ingestion or absorption)?

Stage 3: Adding details to the scenario, creating an overview of resources available to fictional biological weapons program

- Division of resource categories: equipment, personnel, information, and capital
- Critical facilities (equipment, capital): Small non-state group or individual acquiring vs state actor setting up clandestine facilities vs diversion from industry
- Organization (personnel): especially if state actors are involved, useful to understand involvement of different institutions (military, national research, industry), including in the development of a delivery system and in deployment/use operations.

Bibliography

Ad Hoc Group of Governmental Experts to Identify and Examine Potential Verification Measures from a Scientific and Technical Standpoint (1993) *BWC/CONF.III/VEREX/9*. [online]. Available from: https://front.un-arm.org/wp-content/uploads/2020/12/BWC_CONF.III_VEREX_09.pdf (Accessed 20 March 2025).

Anon (1986) *Final Document of the Second Review Conference of the Parties to the BWC*. [online]. Available from: https://docs-library.unoda.org/Biological_Weapons_Convention_-_Second_Review_Conference_(1986)/BWC_CONF.II_13.pdf (Accessed 12 September 2025).

Anon (2024) *On a Special Conference and the ICA and S&T mechanisms*. [online]. Available from: https://docs.un.org/en/BWC/WG/5/WP.21 (Accessed 17 March 2025).

Anon (n.d.) *Development and Evolution of PCR* [online]. Available from: https://www.genengnews.com/insights/development-and-evolution-of-pcr/ (Accessed 17 March 2025).

Anon (n.d.) *Home – Techbiot* [online]. Available from: https://techbiot.eu/#about (Accessed 10 March 2025).

Anon (n.d.) *Landsat Data Access | U.S. Geological Survey* [online]. Available from: https://www.usgs.gov/landsat-missions/landsat-data-access (Accessed 17 March 2025).

Anon (n.d.) *Project BEACON: Using OSINT methods in BWC verification – BlueDot Impact* [online]. Available from: https://biosecurityfundamentals.com/projects/project-beacon-using-osint-methods-in-bwc-verification/ (Accessed 10 March 2025).

Anon (2002) *TREATY ON OPEN SKIES*.

Appen (2024) *The State of AI in 2024 Navigating Challenges and Embracing Opportunities*.

Appleton, E. et al. (2022) *Feasibility of on-site verification*. [online]. Available from: https://static.igem.org/websites/responsibility/2022/bwc-verification/ssrn-id4213018-feasibility-of-on-site-verification.pdf (Accessed 10 March 2025).

Axe, D. (2024) Russia has expanded site of past bioweapons research, satellite images show. *The Washington Post*. 25 October. [online]. Available from: https://www.washingtonpost.com/national-security/interactive/2024/russia-biological-chemical-weapons-laboratory-expansion/ (Accessed 10 March 2025).

Axe, D. (2024) Russia has expanded site of past bioweapons research, satellite images show. *The Washington Post*. 25 October. [online]. Available from: https://www.washingtonpost.com/national-security/interactive/2024/russia-biological-chemical-weapons-laboratory-expansion/ (Accessed 10 March 2025).

Axon Enterprise, Inc. (2023) *The complete history of drones for police and law enforcement* [online]. Available from: https://www.axon.com/resources/history-of-drones (Accessed 19 March 2025).

Bhalla, N. et al. (2016) Introduction to biosensors. *Essays in Biochemistry*. [Online] 60 (1), 1. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC4986445/ (Accessed 20 March 2025).

BioFire Defense (2025) *The BIOFIRE ® SPOTFIRE ® System* [online]. Available from: https://www.biofiredefense.com/products/biofire-spotfire/ (Accessed 21 March 2025).

Biosecure & IAP (2016) *The Biological and Toxin Weapons Convention: Implications of advances in science and technology*. [online]. Available from: https://royalsociety.org/-/media/policy/projects/biological-toxin-weapons-convention/biological-weapons-technical-document.pdf (Accessed 10 March 2025).

Block, L. (2023) To cite this article: Ludo Block (2024) The long history of OSINT. *Journal of Intelligence History*. [Online] 23 (2), 95–109. [online]. Available from: https://www.tandfonline.com/action/journalInformation?journalCode=rjih20 (Accessed 18 March 2025).

Bonah, E. et al. (2019) Application of Hyperspectral Imaging as a Nondestructive Technique for Foodborne Pathogen Detection and Characterization. *Foodborne Pathogens and Disease*. [Online] 16 (10), 712. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC6785170/ (Accessed 10 March 2025).

Budowle, B. et al. (2014) Validation of high throughput sequencing and microbial forensics applications. *Investigative Genetics 2014 5:1*. [Online] 5 (1), 1–18. [online]. Available from: https://investigativegenetics.biomedcentral.com/articles/10.1186/2041-2223-5-9 (Accessed 13 March 2025).

Buse, S. et al. (2022) *A Model Compliance Regime for the Biological Weapons Convention*. [online]. Available from: https://dx.doi.org/10.2139/ssrn.4430388 (Accessed 10 March 2025).

Carter, D. et al. (2020) Global public health surveillance using media reports: Redesigning GPHIN. *Studies in Health Technology and Informatics*. [Online] 270843–847. [online]. Available from: https://pubmed.ncbi.nlm.nih.gov/32570501/ (Accessed 24 June 2025).

Chalmers, H. & Wingo, H. (2024) *Enforcing the Comprehensive Nuclear-Test-Ban Treaty: The Role of Consultation and Clarification*. [online]. Available from: www.opennuclear.orgwww.vertic.org (Accessed 12 September 2025).

Chevrier, M. I. (2020) Compliance mechanisms and their implementation: the contrast between the Biological and Chemical Weapons Conventions. *The Nonproliferation Review*. [Online] 27 (4–6), 475–486. [online]. Available from: https://www.tandfonline.com/doi/abs/10.1080/10736700.2020.1878666 (Accessed 13 March 2025).

Cropper, N. et al. (2022) *Creating a Verification Protocol for the Biological Weapons Convention: A MODULAR-INCREMENTAL APPROACH*. [online]. Available from: https://www.nti.org/wp-content/uploads/2022/06/Creating-a-Verification-Protocol_FINAL_June2022.pdf (Accessed 10 March 2025).

Davies, P. (2024) ChatGPT, Grok, Gemini and other AI chatbots are spewing Russian misinformation, study finds. *Euronews*. 18 June. [online]. Available from: https://www.euronews.com/next/2024/06/18/chatgpt-grok-gemini-and-other-ai-chatbots-are-spewing-russian-misinformation-study-finds (Accessed 24 June 2025).

Ferreira, L. da C. et al. (2024) Hyperspectral imaging for the detection of plant pathogens in seeds: recent developments and challenges. *Frontiers in Plant Science*. [Online] 151387925.

Fradkov, A. (2020) Early History of Machine Learning. *IFAC PapersOnLine*. 53 (2), 1385–1390. [online]. Available from: https://pdf.sciencedirectassets.com/313346/1-s2.0-S2405896321X0002X/1-s2.0-S2405896320325027/main.pdf (Accessed 22 May 2025).

Franco-Duarte, R. et al. (2019) Advances in Chemical and Biological Methods to Identify Microorganisms—From Past to Present. *Microorganisms*. [Online] 7 (5), 130. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC6560418/ (Accessed 20 March 2025).

Goldman, D. & Domschke, K. (2014) *Making sense of deep sequencing*. [Online] [online]. Available from: https://academic.oup.com/ijnp/article/17/10/1717/2357198 (Accessed 19 March 2025).

Haidt, J. (2024) *The Anxious Generation: How the Great Rewiring of Childhood Is Causing an Epidemic of Mental Illness*. Penguin. [online]. Available from: https://www.amazon.co.uk/Anxious-Generation-Rewiring-Childhood-Epidemic-ebook/dp/B0CGWS3JQ6 (Accessed 6 October 2025).

Hanham, M. (2015) *Kim Jong Un Tours Pesticide Facility Capable of Producing Biological Weapons* [online]. Available from: https://www.38north.org/2015/07/mhanham070915/ (Accessed 12 September 2025).

Hanham, M. (2020) *Emerging Trends in Commercial Remote Sensing for Nuclear Arms Control*. [online]. Available from: https://unidir.org/wp-content/uploads/2023/05/Science-and-Technology-for-Monitoring-and-Investigation-of-WMD-Compliance.pdf (Accessed 17 March 2025).

Haulman, D. (2003) *U.S. Unmanned Aerial Vehicles in Combat, 1991-2003*. [online]. Available from: https://www.dafhistory.af.mil/Portals/16/documents/Studies/AFD-070912-042.pdf (Accessed 19 March 2025).

Higgs, M. (2024) *The Latest Developments in Sequencing Technologies* [online]. Available from: https://frontlinegenomics.com/the-latest-developments-in-sequencing-technologies/ (Accessed 10 March 2025).

ICEYE (2025) *Accurate, near real-time Earth monitoring with SAR data*. [online]. Available from: https://www.iceye.com/hubfs/Downloadables/SAR_Data_Brochure_ICEYE.pdf (Accessed 17 March 2025).

International Organization for Standardization (n.d.) *What is artificial intelligence (AI)?* [online]. Available from: https://www.iso.org/artificial-intelligence/what-is-ai (Accessed 22 May 2025).

Kaszeta, D. (2021) Small-Scale Chemical and Biological Production: Current Threats and Future Trajectories. Royal United Services Institute [online]. Available from: https://www.rusi.org/explore-our-research/publications/occasional-papers/small-scale-chemical-and-biological-production-current-threats-and-future-trajectories (Accessed 6 October 2025).

Kelle, A. & Dando, M. R. (2025) Behavioral arms control in the century of biology. *The Nonproliferation Review*. [Online] 1–21. [online]. Available from: /doi/pdf/10.1080/10736700.2025.2505828?download=true (Accessed 6 October 2025).

Kelle, A. & Dando, M. R. (2025) Behavioral arms control in the century of biology. *The Nonproliferation Review*. [Online] 1–21. [online]. Available from: https://www.tandfonline.com/doi/pdf/10.1080/10736700.2025.2505828 (Accessed 9 September 2025).

Kimball, D. (2024) *The Biological Weapons Convention (BWC) At A Glance* [online]. Available from: https://www.armscontrol.org/factsheets/biological-weapons-convention-bwc-glance-0 (Accessed 21 March 2025).

Knight, W. (2025) Google's AI Boss Says Gemini's New Abilities Point the Way to AGI. WIRED [online]. Available from: https://www.wired.com/story/googles-ai-boss-says-geminis-new-abilities-point-the-way-to-agi/ (Accessed 22 May 2025).

Kuhn, U. & Williams, H. (2023) A New Approach to Arms Control. Foreign Affairs [online]. Available from: https://www.foreignaffairs.com/united-states/new-approach-arms-control (Accessed 6 October 2025).

Kundaliya, D. (2025) *OpenAI shutters ChatGPT accounts used by Russian, Chinese, Iranian hacker groups* [online]. Available from: https://www.computing.co.uk/news/2025/security/openai-shutters-hacker-chatgpt-accounts (Accessed 24 June 2025).

Li, C. N. & Nakamura, M. M. (2022) Utility of Broad-Range PCR Sequencing for Infectious Diseases Clinical Decision Making: a Pediatric Center Experience. *Journal of Clinical Microbiology*. [Online] 60 (5), e02437-21. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC9116169/ (Accessed 21 March 2025).

Littlewood, J. & Lentzos, F. (2022) *Russia's alleged bioweapons claims have few supporters* [online]. Available from: https://thebulletin.org/2022/10/russias-alleged-bioweapons-claims-have-few-supporters/ (Accessed 17 September 2025).

Liu, N. (2022) *Everything you ever wanted to know about SAR satellite data and the ecosystem but were afraid to ask* [online]. Available from: https://geoawesome.com/eo-hub/everything-you-ever-wanted-to-know-about-sar-satellite-data-and-the-ecosystem-but-were-afraid-to-ask/ (Accessed 17 March 2025).

Liu, Y. (2025) Discovering topics and trends in biosecurity law research: A machine learning approach. *One Health*. [Online] 20100964.

Lu, B. et al. (2020) Recent Advances of Hyperspectral Imaging Technology and Applications in Agriculture. *Remote Sensing*. [Online] 12 (2659). [online]. Available from: www.mdpi.com/journal/remotesensing (Accessed 18 March 2025).

McLeish, C. & Moon, J. R. (2020) Sitting on the boundary: the role of reports in investigations into alleged biological-weapons use. *The Nonproliferation Review*. [Online] 27 (4–6), 525–540. [online]. Available from: https://www.tandfonline.com/doi/abs/10.1080/10736700.2020.1872968 (Accessed 6 October 2025).

Meier, O. (2006) *Aerial Surveillance and BWC Compliance Monitoring*.

Meselson M, Guillemin J, Hugh-Jones M, Langmuir A, Popova I, Shelokov A, Yampolskaya O. (1994) The Sverdlovsk anthrax outbreak of 1979. *Science*. Nov 18;266(5188):1202-8. doi: 10.1126/science.7973702. PMID: 7973702.

Miller, K. et al. (2018) *Capabilities of the Acquisition Path Analysis Tool (APAT) for Integration of Multisource Data*. p.105–105. [online]. Available from: https://inis.iaea.org/records/51m7j-vyf39 (Accessed 6 October 2025).

Nakao, A. et al. (2015) *Acquisition Path Analysis as a Collaborative Activity*. p.209–209. [online]. Available from: https://inis.iaea.org/records/x3jos-psm72 (Accessed 6 October 2025).

NASA (n.d.) *Landsat 9 Bands* [online]. Available from: https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-bands/ (Accessed 17 March 2025a).

NASA (n.d.) *RADARSAT-1* [online]. Available from: https://www.earthdata.nasa.gov/data/platforms/space-based-platforms/radarsat-1 (Accessed 17 March 2025b).

National Human Genome Research Institute (2024) *Human Genome Project Fact Sheet* [online]. Available from: https://www.genome.gov/about-genomics/educational-resources/fact-sheets/human-genome-project (Accessed 21 March 2025).

O'Brien, J. T. & Nelson, C. (2020) Assessing the Risks Posed by the Convergence of Artificial Intelligence and Biotechnology. *Health security*. [Online] 18 (3), 219–227. [online]. Available from: https://pubmed.ncbi.nlm.nih.gov/32559154/ (Accessed 6 October 2025).

Park, S. & Puccioni, A. (2024) *North Korea's Pursuit of an ELWR: Potential Power in Nuclear Ambitions?* [online]. Available from: https://www.38north.org/2024/01/north-koreas-pursuit-of-an-elwr-potential-power-in-nuclear-ambitions/ (Accessed 20 March 2025).

Planet Labs (n.d.) *Detect, Monitor, and Minimize Risk Across Large Geographic Areas* [online]. Available from: https://www.planet.com/solutions/broad-area-management/ (Accessed 17 March 2025).

Ralf Trapp (2023) Chemical and microbiological forensics in investigations of alleged uses of chemical and biological weapons – a preliminary analysis, CBWNet Working Paper No. 4. https://cbwnet.org/media/pages/publications/working-paper/chemical-and-microbiological-forensics/ea2a53e0f3-1676557423/2023-0216_wp-4_trapp-forensics_web.pdf

Revill, J. (2022) *The Past, Present and Future of BWC Article V Consultations → UNIDIR* [online]. Available from: https://unidir.org/the-past-present-and-future-of-bwc-article-v-consultations/ (Accessed 12 September 2025).

Revill, J. (n.d.) *Compliance Revisited: An Incremental Approach to Compliance in the Biological and Toxin Weapons Convention*. [online]. Available from: www.miis.edu (Accessed 10 March 2025).

Revill, J. et al. (2022) *WMD COMPLIANCE ENFORCEMENT SERIES BACK TO THE FUTURE FOR VERIFICATION IN THE BIOLOGICAL DISARMAMENT REGIME?* [online]. Available from: www.unidir.org| (Accessed 10 March 2025).

SatVu (2023) *World first in high resolution satellite thermal imaging defines new era of climate monitoring* [online]. Available from: https://www.satellitevu.com/news/world-first-in-high-resolution-satellite-thermal-imaging-defines-new-era-of-climate-monitoring (Accessed 17 March 2025).

SatVu (2025) *SatVu's HotSat-1 Archive Available to U.S. Government Agencies Through The Global Data Marketplace* [online]. Available from: https://www.satellitevu.com/news/satvus-hotsat-1-archive-available-to-u-s-government-agencies-through-the-global-data-marketplace (Accessed 17 March 2025).

Schmedes, S. & Budowle, B. (2019) Microbial Forensics. *Encyclopedia of Microbiology*. [Online] 134. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC7149751/ (Accessed 10 March 2025).

Shearer, M. P. et al. (2022) BWC assurance: increasing certainty in BWC compliance. *Nonproliferation Review*. [Online] 29 (1–3), 47–75. [online]. Available from: /doi/pdf/10.1080/10736700.2023.2178099?download=true (Accessed 12 September 2025).

Singhal, N. et al. (2015) MALDI-TOF mass spectrometry: an emerging technology for microbial identification and diagnosis. *Frontiers in Microbiology*. [Online] 6 (AUG), 791. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC4525378/ (Accessed 20 March 2025).

Stringham, C. et al. (2024) *Full-resolution SLC Imagery: Revolutionizing Commercial SAR Data* [online]. Available from: https://www.capellaspace.com/blog/full-resolution-slc-imagery-revolutionizing-commercial-sar-data (Accessed 17 March 2025).

Stryker, C. & Holdsworth, J. (2024) *What Is NLP (Natural Language Processing)?* [online]. Available from: https://www.ibm.com/think/topics/natural-language-processing (Accessed 24 June 2025).

Suresh, N. (n.d.) *Final Report for the Tabletop Exercise* [online]. Available from: https://luxurious-quokka-033.notion.site/Final-Report-for-the-Tabletop-Exercise-af639d909c16475e90fod49727397e09 (Accessed 18 March 2025).

ThermoFisher Scientific (n.d.) *Overview of Mass Spectrometry* [online]. Available from: https://www.thermofisher.com/uk/en/home/life-science/protein-biology/protein-biology-learning-center/protein-biology-resource-library/pierce-protein-methods/overview-mass-spectrometry.html (Accessed 20 March 2025a).

ThermoFisher Scientific (n.d.) *The History of PCR* [online]. Available from: https://www.thermofisher.com/uk/en/home/brands/thermo-scientific/molecular-biology/molecular-biology-learning-center/molecular-biology-resource-library/spotlight-articles/history-pcr.html (Accessed 17 March 2025b).

Thompson, J. F. & Milos, P. M. (2011) The properties and applications of single-molecule DNA sequencing. *Genome Biology*. [Online] 12 (2), 1–10. [online]. Available from: https://genomebiology.biomedcentral.com/articles/10.1186/gb-2011-12-2-217 (Accessed 12 March 2025).

treangenlab (2021) *PlasmidHawk* [online]. Available from: https://gitlab.com/treangenlab/plasmidhawk (Accessed 20 March 2025).

Turgeon, T. (2024) *Radio Frequency Collection: Securing the Maritime Domain* [online]. Available from: https://www.darkshipping.com/post/securing-the-maritime-domain-with-rf-data (Accessed 20 March 2025).

Tytgat, O. (2022) *Bringing Science to the Scene: Novel strategies for portable DNA profiling*. Ghent, Belgium: Ghent University. [online]. Available from: https://www.researchgate.net/profile/Olivier-Tytgat/publication/362991666_Bringing_Science_to_the_Scene_Novel_strategies_for_portable_DNA_profiling/links/630bf70dacd814437fe479ea/Bringing-Science-to-the-Scene-Novel-strategies-for-portable-DNA-profiling.pdf (Accessed 10 March 2025).

VERTIC & UNIDIR (2003) *Coming to Terms with Security: A Handbook on Verification and Compliance*. [online]. Available from: https://www.vertic.org/media/assets/Handbook.pdf (Accessed 10 March 2025).

Walker, J. R. (2020) Reflections on the 2001 BWC Protocol and the verification challenge. *The Nonproliferation Review*. [Online] 27 (4–6), 507–515. [online]. Available from: https://www.tandfonline.com/doi/abs/10.1080/10736700.2020.1865635 (Accessed 13 March 2025).

Wang, Q. et al. (2021) PlasmidHawk improves lab of origin prediction of engineered plasmids using sequence alignment. *Nature Communications 2021 12:1*. [Online] 12 (1), 1–12. [online]. Available from: https://www.nature.com/articles/s41467-021-21180-w (Accessed 20 March 2025).

Wheeler, N. (2025) *AMR and Emerging Biotechnologies*. [online]. Available from: https://doi.org/10.71706/6623f95c-4a10-49b4-afd2-a708792d5e10 (Accessed 21 March 2025).

Wilson, H. & Smidovich, N. (2021) Perspectives on UNSCOM and UNMOVIC: An interview with Nikita Smidovich. *Bulletin of the Atomic Scientists*. [Online] 77 (4), 184–187. [online]. Available from: https://www.tandfonline.com/doi/abs/10.1080/00963402.2021.1941564 (Accessed 13 March 2025).

Wilton Park (2022) *Emerging technologies and the Nuclear Non-Proliferation Treaty In partnership with the Stanley Center for Peace and Security, and King's College London with support from the MacArthur Foundation*. [Online]. Available from: https://www.wiltonpark.org.uk/event/emerging-technologies-and-the-nuclear-nonproliferation-treaty/. (Accessed 10 March 2025).

Withorne, J. (2020) *Machine Learning Applications in Nonproliferation: Assessing Algorithmic Tools for Strengthening Strategic Trade Controls*. [online]. Available from: www.nonproliferation.org/dc (Accessed 10 March 2025).

Wurtz, N. et al. (2023) Simple Wastewater Preparation Protocol Applied to Monitor the Emergence of the Omicron 21L/BA.2 Variant by Genome Sequencing. *Viruses*. [Online] 15 (2), 268. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC9965846/ (Accessed 17 March 2025).

Yang, S. & Rothman, R. E. (2004) PCR-based diagnostics for infectious diseases: uses, limitations, and future applications in acute-care settings. *The Lancet. Infectious Diseases*. [Online] 4 (6), 337. [online]. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC7106425/ (Accessed 21 March 2025).

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