WMD COMPLIANCE & ENFORCEMENT SERIES
PAPER EIGHT

SCIENCE AND TECHNOLOGY

FOR MONITORING AND INVESTIGATION OF WMD COMPLIANCE

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ABBREVIATIONS AND ACRONYMS

AI	Artificial Intelligence
AIS	Automatic identification system
BWC	Biological and Toxin Weapons Convention
CAS	Chemical Abstract Service
CWA	Chemical Warfare Agent
CWC	Chemical Weapons Convention
DESIS	Deutsches Zentrum für Luft- und Raumfahrt (DLR) Earth Sensing Imaging Spectrometer
HS	Harmonized System
IAEA	International Atomic Energy Agency
OPCW	Organisation for the Prohibition of Chemical Weapons
NPT	Non-Proliferation Treaty
SAB	Scientific Advisory Board (OPCW)
SAR	Synthetic Aperture Radar
TWG	Temporary Working Group
UAV	Uncrewed Aerial Vehicle
UGV	Uncrewed Ground Vehicle
UNSCOM	United Nations Special Commission
WCO	World Customs Organization
WMD	Weapon of Mass Destruction

SUMMARY

The integration of novel technologies for monitoring and investigating compliance can enhance the effectiveness of regimes related to weapons of mass destruction (WMD). This report looks at the potential role of four novel approaches based on recent technological advances – remote sensing tools; open-source satellite data; open-source trade data; and artificial intelligence (AI) – in monitoring and investigating compliance with WMD treaties. The report consists of short essays from leading experts that introduce particular technologies, discuss their applications in WMD regimes, and consider some of the wider economic and political requirements for their adoption.

The growing number of space-based sensors is raising confidence in what open-source satellite systems can observe and record. These systems are being combined with local knowledge and technical expertise through social media platforms, resulting in dramatically improved coverage of the Earth's surface. These open-source tools can complement and augment existing treaty verification and monitoring capabilities in the nuclear regime.

Remote sensing tools, such as uncrewed vehicles, can assist investigators by enabling the remote collection of data and chemical samples. In turn, this data can provide valuable indicators, which, in combination with other data, can inform assessments of compliance with the chemical weapons regime. In addition, remote sensing tools can provide inspectors with real time two- or three-dimensional images of a site prior to entry or at the point of inspection. This can facilitate on-site investigations.

In the past, trade data has proven valuable in informing assessments of non-compliance with the biological weapons regime. Today, it is possible to analyse trade data through online, public databases. In combination with other methods, open-source trade data could be used to detect anomalies in the biological weapons regime.

AI and the digitization of data create new ways to enhance confidence in compliance with WMD regimes. In the context of the chemical weapons regime, the digitization of the chemical industry as part of a wider shift to Industry 4.0 presents possibilities for streamlining declarations under the Chemical Weapons Convention (CWC) and for facilitating CWC regulatory requirements. AI tools and digitization could further enable sampling and analysis of scheduled chemicals for CWC verification purposes by collecting, integrating and analysing multiple streams of remote sensing data from a diversity of sensor types. Data analytics that enable diagnosis of plant diseases from digital images of plant stress are intriguing as a method to recognize signatures of a toxic chemical exposure. Similar approaches might be used to identify chemical weapons agents among recovered old and abandoned munitions.

The adoption of new technologies in WMD-related regimes is neither inevitable nor immediate. It depends on the fulfilment of wider economic, political and technical requirements. To be effective, States and the international organizations dedicated to WMD treaties may require

access to external expertise and new equipment. These organizations will also need to validate both the technologies and the methods for using these technologies to ensure that they are sufficiently robust. Additional tools with which to manage ever-growing amounts of data from an expanding range of sources may also be required. The integration of new compliance-related technologies may further require overcoming challenges in the structural and organizational culture of international organizations.

The successful adoption of new technologies in support of WMD treaty compliance also requires States and stakeholders to undertake a realistic evaluation of relative advantages (and disadvantages) of these novel technologies. Such an evaluation needs to consider the limits of technological "solutions", the integrity of data they produce, the extent of intrusiveness and the financial costs.

1 INTRODUCTION

For regimes tasked with curbing so-called weapons of mass destruction (WMD) – that is, nuclear, biological and chemical weapons – adapting to changes in science and technology raises perennial challenges. One challenge is that such developments can tip the balance in favour of proliferation, for instance, by creating new, undetected pathways to acquiring proscribed weapons. A parallel concern is that a cluster of scientific and technological breakthroughs might rapidly undermine specific WMD-related regimes at a stroke by making it easier for those with hostile intent to develop these weapons. Moreover, in the face of such challenges, every WMD-related regime has finite resources: each faces real constraints both in practical terms and in terms of how much sustained political attention it can command from the international community.

Nonetheless, advances in science and technology present opportunities as well as risks for WMD regimes. This report focuses on what new or hitherto underexplored technologies could offer in relation to monitoring and investigating compliance with WMD-related treaties such as the 1968 Treaty on the Non-Proliferation of Nuclear Weapons (NPT), the 1972 Bacteriological (Biological) and Toxin Weapons Convention (BWC), and the 1993 Chemical Weapons Convention (CWC). To better understand these opportunities, the report comprises four short essays that provide an overview of four new approaches based on recent technological advances that have been, or could be, applied in support of monitoring or investigating compliance. These technologies are remote sensing tools, open-source satellite data, open-source trade data and artificial intelligence (AI), in conjunction with the digitization of data.

These essays have been written by leading experts in each of these technological areas. Each essay provides an accessible introduction to the technology and highlights its potential utility for compliance and enforcement of WMD regimes. It then offers reflections on the wider economic and political requirements for the adoption of the technology.

The first essay explores remote sensing technology in the context of the chemical weapons regime. This essay is written by the members of the Temporary Working Group (TWG) on Investigative Science and Technology of the Scientific Advisory Board (SAB) of the Organisation for the Prohibition of Chemical Weapons (OPCW). The contribution was led by Veronica Borrett, the TWG Chairperson, and was co-authored by other TWG members: Crister Åstot, Augustin Baulig, Christophe Curty, Brigitte Dorner, Carlos Fraga, Jonathan Forman, David Gonzalez, Robert Mikulak, Daan Noort, Syed K. Raza, Cheng Tang, Christopher Timperley, Francois van Straten, Ed van Zalen, Paula Vanninen and Farhat Waqar. The essay discusses, among other things, the increasingly important role of remote sensing tools such as chemical sensors mounted on uncrewed aerial vehicles (UAVs), GPS-enabled video cameras and social media in support of non-routine OPCW missions. It further identifies some of the wider requirements for the effective use of such technologies.

Melissa Hanham of the Open Nuclear Network looks at the role of open-source satellite data in monitoring and investigation in the nuclear weapons regime in the second essay. She highlights how open-source satellite systems are being combined with local knowledge and technical expertise through social media platforms. The data generated through these processes could complement and augment existing treaty verification and monitoring capabilities.

In the third essay, Gunnar Jeremias, Head of the Research Group for Biological Arms Control, University of Hamburg, looks at how open-source trade data can be used in conjunction with other data to detect anomalies that may be indicative of a biological weapons programme. He also highlights some new ways in which trade data could be more effectively harnessed in support of assessments of compliance with the biological weapons regime.

Jonathan Forman was the OPCW's Science Policy Adviser from 2013-2019 where he had also served as Secretary to its SAB. In the fourth essay, drawing on the work he did with the SAB he writes on how digitization and AI might provide opportunities to enhance the implementation of the CWC. Forman highlights how such tools could generate data that informs decisions of considerable consequence for treaty implementation and the corresponding importance of validating technologies for use in compliance monitoring and investigative purposes.

In the final section of this report, James Revill and John Borrie draw out cross-cutting themes from the essays, paying attention to the organizational, political and economic requirements for the further integration of monitoring and investigative technologies into WMD regimes.

2 REMOTE SENSING AND THE IMPLEMENTATION OF THE CHEMICAL WEAPONS CONVENTION

In recent years, experts from the Organisation for the Prohibition of Chemical Weapons (OPCW), the implementing body of the Chemical Weapons Convention (CWC), have been tasked to carry out investigations of alleged use of chemical weapons or other non-routine missions.[1] In 2017, the OPCW Director-General requested his Scientific Advisory Board (SAB) to conduct an in-depth review of methods and technologies relevant to such investigative work.[2] This essay outlines the findings of the SAB's Temporary Working Group (TWG) on Investigative Science and Technology.[3]

2.1 INTRODUCTION TO REMOTE SENSING

Remote sensing tools assist investigators by enabling them to collect data and samples without the need for personnel to make direct contact with the incident site. Examples of such tools and the types of information they might collect include:

- **Robotic devices or uncrewed aerial/ground vehicles (UAVs/UGVs).** While robotic devices on their own are not remote sensors, they can be fitted with sensors that send signals for data collection. These tools can also be equipped to collect physical samples for analysis (e.g. bringing a remote sample to the analysts).
- **Technologies that can acquire data indicative of the presence of or previous exposure to a chemical agent from afar.** Relevant signatures could come from spectral analysis or imaging (Raman, infrared, hyperspectral, LIDAR etc.) as well as visibly observable signs of chemical reaction such as colour change, oxidation, or unusual or unexpected environmental stress.
- **Public health information.** After an incident, this can include reports of unusual injuries or symptoms observed by emergency responders or on hospital admission.

[1] OPCW, "Mission: A World Free of Chemical Weapons", https://www.opcw.org/about-us/mission.

[2] OPCW, "Scientific Advisory Board: Keeping Pace with Scientific and Technological Change", https://www.opcw.org/about-us/subsidiary-bodies/scientific-advisory-board.

[3] OPCW, "Summary of the First Meeting of the Scientific Advisory Board's Temporary Working Group on Investigative Science and Technology", SAB-27/WP.1, 26 February 2018, https://www.opcw.org/sites/default/files/documents/SAB/en/sab-27-wp01_e_.pdf; OPCW, "Summary of the Second Meeting of the Scientific Advisory Board's Temporary Working Group on Investigative Science and Technology", SAB-28/WP.2, 21 January 2019, https://www.opcw.org/sites/default/files/documents/2019/01/sab28wp02(e).pdf; OPCW, "Summary of the Third Meeting of the Scientific Advisory Board's Temporary Working Group on Investigative Science and Technology", SAB-28/WP.3, 4 June 2019, https://www.opcw.org/sites/default/files/documents/2019/06/sab-28-wp03(e).pdf; OPCW, "Summary of the Fourth Meeting of the Scientific Advisory Board's Temporary Working Group on Investigative Science and Technology", SAB-29/WP.1, 25 November 2019, https://www.opcw.org/sites/default/files/documents/2019/11/sab-29-wp01(e).pdf; and OPCW, Investigative Science and Technology, Report of the Scientific Advisory Board's Temporary Working Group, SAB/REP/1/19, December 2019, https://www.opcw.org/sites/default/files/documents/2020/11/TWG%20Investigative%20Science%20Final%20Report%20-%20January%202020%20%281%29.pdf

- **Satellite data (including multispectral and thermal imagery).** This may reveal suspect activities (movements, objects) or chemical plumes[4] or other signatures of chemical release.
- **Photos or videos of activities and items that are provided to investigators or shared through social media.**[5]

These tools and data can provide valuable indicators which, in combination with other information streams, can help inform assessments of compliance. As part of an investigation, the information may also provide leads for other investigative steps or be used as evidence. In addition, the remote digitization of investigative sites can assist in ensuring site integrity, as discussed further in Section 2.5.

2.2 INCREASING IMPORTANCE OF REMOTE SENSING IN THE OPCW

Since 2013, the OPCW has increasingly been tasked to undertake non-routine missions in which on-site detection and analysis has been difficult.[6] In contrast to OPCW routine inspection missions, non-routine or Fact-Finding Missions (FFMs) may be conducted under conditions that are unfamiliar, hard-to-predict, physically difficult and dangerous. Inspectors may not

[4] E.g. O. Björnham, H. Grahn and N. Brännström, "Reconstructing Chemical Plumes from Stand-off Detection Data of Airborne Chemicals Using Atmospheric Dispersion Models and Data Fusion", Pure and Applied Chemistry, vol. 90, no. 10, October 2018, pp. 1577–1592, https://doi.org/10.1515/pac-2018-0101; and O. Björnham et al. "The 2016 Al-Mishraq Sulphur Plant Fire: Source and Health Risk Area Estimation", Atmospheric Environment, vol. 169, November 2017, pp. 287–296, https://doi.org/10.1016/j.atmosenv.2017.09.025.

[5] E.g. EyeWitness to Atrocities, "What We Believe", https://www.eyewitness.global/about-us; University of California, Berkeley, Human Rights Center, "Human Rights Center Investigations Lab: Where Facts Matter", https://humanrights.berkeley.edu/programs-projects/tech/investigations-lab; and Global Legal Action Network, "Digital Evidence, Blockchain, and Air-strikes in Yemen", 15 March 2018, https://www.glanlaw.org/single-post/2018/03/15/New-project-Digital-evidence-blockchain-and-air-strikes-in-Yemen.

[6] These have included verifying the removal and destruction of chemical weapons as well as Fact-Finding Missions (FFMs) and Technical Assistance Visits (TAVs). Furthermore, in June 2018, the Special Conference of the States Parties to the Convention tasked the OPCW Director-General to "put in place arrangements to identify the perpetrators of the use of chemical weapons" under specified circumstances. In addition, the Director-General was mandated to provide "technical expertise to identify those who were perpetrators, organisers, sponsors or otherwise involved in the use of chemicals as weapons" to any State party that was investigating the possible use of chemical weapons on its territory and requested such assistance. OPCW, Conference of the States Parties, "Decision: Addressing the Threat from Chemical Weapons Use", C-SS-4/DEC.3, 27 June 2018, paragraphs 10, 20, https://www.opcw.org/sites/default/files/documents/CSP/C-SS-4/en/css4dec3_e_.doc.pdf.

be able to visit the site of an incident or to meet with affected individuals because locations are remote, access physically difficult, or the physical security or health of inspectors would be placed at too great a risk. Thus, alternative means of collecting information, other than through direct physical access to a site, need to be identified, assessed and considered.

2.3 SELECTED REMOTE SENSING TOOLS

Several remote sensing tools are of use. On-site detection and identification of a chemical warfare agent (CWA) or site can be performed with a range of commercial systems. Detectors can also be used to pin-point optimal sites for taking samples for later off-site analysis by OPCW Designated Laboratories.[7] There are examples of stand-off detection platforms.[8] However, another approach is the integration of on-site detectors or sensing systems onto UAVs or UGVs.[9] The availability of smaller, or miniaturized, detectors and the development of UAVs and UGVs has allowed off-the-shelf and specially designed CWA detectors to be used as payloads; and for UAVs and UAGs to be fitted with sampling systems. Data collected by UAVs and/or UGVs can be integrated with data collected by other remote monitoring equipment[10] and with satellite imagery[11] in real-time.

Analysis of high-resolution satellite imagery from commercial sources has already demonstrated its value in OPCW fact-finding efforts and in other arms control and non-proliferation contexts

[7] OPCW, "Designated Laboratories", https://www.opcw.org/designated-laboratories.

[8] OPCW, "Report of the Scientific Advisory Board's Workshop on Emerging Technologies", SAB-26/WP.1, 21 July 2017, https://www.opcw.org/sites/default/files/documents/SAB/en/sab26wp01_SAB.pdf; and J. E. Forman et al., "Innovative Technologies for Chemical Security", Pure and Applied Chemistry, vol. 90, no. 10, October 2018, pp. 1527–1557, https://doi.org/10.1515/pac-2018-0908.

[9] See B. B. Barnes, "Environmental Applications of Small Unmanned Aircraft Systems in Multi Service Tactics, Techniques, and Procedures for Chemical, Biological, Radiological, and Nuclear Reconnaissance and Surveillance", Theis, AFIT-ENV-MS-17-M-170, Air Force Institute of Technology, March 2017, https://apps.dtic.mil/docs/citations/AD1055173; and S. Everts and M. Davenport, "Drones Swarm to Science", Chemical & Engineering News, vol. 94, no, 9, 29 February 2016, pp. 32–33. See also other articles cited in this chapter; D.R. López et al., "Data Gathering in Crisis Management", in 2019 International Conference on Information and Communication Technologies for Disaster Management (ICT-DM), IEEE 2019, pp. 1–8; D. Di Giovanni, F. Fumian and A. Malizia, "Application of Miniaturized Sensors to Unmanned Aerial Vehicles, A New Pathway for the Survey of Critical Areas", Journal of Instrumentation, vol. 14, no, 3, March 2019, p.C03006, https://doi.org/10.1088/1748-0221/14/03/C03006; G.D. Koblentz, "Emerging Technologies and the Future of CBRN Terrorism", Washington Quarterly, vol. 43, no. 2, 2020, pp.177–196, https://doi.org/10.1080/0163660X.2020.1770969; and S. Zampolli et al., "A MEMS-enabled Deployable Trace Chemical Sensor Based on Fast Gas-Chromatography and Quartz Enhanced Photoacousic Spectoscopy", Sensors, vol. 20, no. 1, January 2020, p. 120, https://doi.org/10.3390/s20010120. OPCW, "Summary of the Fourth Meeting of the Scientific Advisory Board's Temporary Working Group on Investigative Science and Technology", SAB-29/WP.1, 25 November 2019, Subitem 10(e), pp. 23–24, https://www.opcw.org/sites/default/files/documents/2019/11/sab-29-wp01(e).pdf 10.20; and OPCW, "Summary of the Third Meeting of the Scientific Advisory Board's Temporary Working Group on Investigative Science and Technology", SAB-28/WP.3, 4 June 2019, Subitem 10(b), pp. 26–27, Subitem 13(b), pp. 32–34, and references therein, https://www.opcw.org/sites/default/files/documents/2019/06/sab-28-wp03(e).pdf.

[10] R. Bogue, "Remote Chemical Sensing: A Review of Techniques and Recent Developments", Sensor Review, vol. 38, no. 4, 2018, pp. 453–457, https://doi.org/10.1108/sr-12-2017-0267; P. Gaudio, "Laser Based Standoff Techniques: A Review on Old and New Perspectives for Chemical Detection and Identification", in M. Martellini and A. Malizia (eds.), Cyber and Chemical, Biological, Radiological, Nuclear, Explosives Challenges, Springer, 2017, pp. 155–177, https://doi.org/10.1007/978-3-319-62108-1_8; K.L. Gares et al., "Review of Explosive Detection Methodologies and the Emergence of Standoff Deep UV Resonance Raman", Journal of Raman Spectroscopy, vol. 47, no. 1 January 2016, https://doi.org/10.1002/jrs.4868; and A. Hakonen et al., "Explosive and Chemical Threat Detection by Surface-Enhanced Raman Scattering: A Review", Analytica Chimica Acta, vol. 893, 17 September 2015, pp. 1–13, https://doi.org/10.1016/j.aca.2015.04.010.

[11] E.g. O. Björnham, H. Grahn and N. Brännström, "Reconstructing Chemical Plumes from Stand-off Detection Data of Airborne Chemicals Using Atmospheric Dispersion Models and Data Fusion", Pure and Applied Chemistry, vol. 90, no. 10, October 2018, pp. 1577–1592, https://doi.org/10.1515/pac-2018-0101; and O. Björnham et al. "The 2016 Al-Mishraq Sulphur Plant Fire: Source and Health Risk Area Estimation", Atmospheric Environment, vol. 169, November 2017, pp. 287–296, https://doi.org/10.1016/j.atmosenv.2017.09.025.

(as discussed in greater depth in the nuclear context by Hanham in section 3 of this report). Historical commercial satellite imagery, which is frequently available,[12] can help assess activities at a site over time, for example, before, during and after an alleged incident.

Under the CWC, all declared chemical weapons are subject to systematic verification through on-site inspection and monitoring. The convention requires continuous presence of OPCW inspectors at chemical weapons destruction sites when the destruction facility is in operation and during key steps in the initial commissioning phase. In recent years, the OPCW has explored and applied remote sensing and verification measures to monitor compliance in non-permissive environments. For example, in 2016, GPS tracking devices were used during a routine chemical weapons removal operation in Libya.[13] Some activities in Libya were live-streamed for OPCW staff.[14]

In the Syrian Arab Republic,[15] the OPCW installed remote monitoring systems at 12 declared chemical weapons production facilities[16] (underground structures). The destruction operations were verified through a combination of the physical presence of the OPCW inspectors and the use of on-site monitoring equipment[17] that continues to operate.[18] By creatively adapting existing technology, the OPCW has also made use of non-OPCW personnel to collect information.[19] For example, sealed, GPS-enabled video cameras, furnished by the OPCW and operated by Syrian Government personnel, were used to monitor destruction activities at chemical weapons production facilities in dangerous locations in the country.[20]

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12 E.g. M. Hanham, et al., Geo4Nonpro 2.0, James Martin Center for Nonproliferation Studies (CNS) Occasional Paper no. 38, Middlebury Institute of International Studies at Monterey, October 2018, https://www.nonproliferation.org/op38-geo4nonpro-2-0/; and G. Liu et al., Eyes on U: Opportunities, Challenges, and Limits of Remote Sensing for Monitoring Uranium Mining and Milling, James Martin Center for Nonproliferation Studies (CNS) Occasional paper no. 44, Middlebury Institute of International Studies at Monterey, January 2018, https://www.nonproliferation.org/op-44-eyes-on-u-opportunities-challenges-and-limits-of-remote-sensing-for-monitoring-uranium-mining-and-milling/.

13 OPCW, "Libya: Modified Concept Plan for Destruction of the Remaining Category 2 Chemical Weapons in Libya", EC-M-52/NAT.1, 25 July 2016.

14 OPCW, "Results of Samples Associated with the Technical Secretariat's Evaluation of the Amended Declaration Submitted by Libya with Regard to the Category 2 Chemical Weapons Stored at the Ruwagha Chemical Weapons Storage Facility", EC-89/S/3, 2 October 2018. Notably this process used non-interrupted recording of the destruction process to monitor the compliance. OPCW, "Technical Secretariat's Evaluation of the Amended Declaration Submitted by Libya with Regard to the Category 2 Chemical Weapons Stored at the Ruwagha Chemical Weapons Storage Facility", EC-83/S/2, 12 August 2016.

15 OPCW, "Progress in the Elimination of the Syrian Chemical Weapons Programme", Note by the Director-General, EC-78/DG.9, 23 February 2015, https://www.opcw.org/sites/default/files/documents/EC/78/en/ec78dg09_e_.pdf.

16 OPCW, "First of 12 Chemical Weapon Production Facilities in Syria Destroyed", News, 3 February 2015, https://www.opcw.org/media-centre/news/2015/02/first-12-chemical-weapon-production-facilities-syria-destroyed.

17 OPCW, "Combined Destruction and Verification Plans for Twelve Declared Chemical Weapons Production Facilities in the Syrian Arab Republic", Note by the Director-General, EC-M-40/DG.2, 27 March 2014.

18 OPCW, "Progress in the Elimination of the Syrian Chemical Weapons Programme", Note by the Director-General, EC-80/DG.20, 23 September 2015, https://www.opcw.org/sites/default/files/documents/EC/80/en/ec80dg20_e_.pdf; OPCW, "Progress in the Elimination of the Syrian Chemical Weapons Programme", Note by the Director-General, EC-81/DG.5, 25 January 2016, https://www.opcw.org/sites/default/files/documents/EC/81/en/ec81dg05_e_.pdf; and OPCW, "Opening Statement by the Director-General to the Ninety-First Session of the Executive Council", EC-91/DG.25, 9 July 2019, paragraph 51, https://www.opcw.org/sites/default/files/documents/2019/07/ec91dg25(e).pdf.

19 E.g. OPCW, "Summary of the Third Meeting of the Scientific Advisory Board's Temporary Working Group on Investigative Science and Technology", SAB-28/WP.3, 4 June 2019, paragraphs 10.1–10.2, https://www.opcw.org/sites/default/files/documents/2019/06/sab-28-wp03(e).pdf.

20 OPCW, "Progress in the Elimination of the Syrian Chemical Weapons Programme", Note by the Director-General, EC-75/DG.6, 25 February 2014, https://www.opcw.org/sites/default/files/documents/EC/75/en/ec75dg06_e_.pdf.

2.4 ADDITIONAL THIRD-PARTY INFORMATION

Increasingly, information potentially relevant to non-routine missions is available from open sources such as social media, YouTube videos and other information; and electronic documents or samples provided by interested parties. Many questions can be raised about the validity of such information, and its authenticity needs to be established, yet it can be valuable for corroborating other information in the reconstruction of a past event.

Extensive expertise in assessing such information, for example, using metadata associated with videos or forensic analysis of digital files and the equipment that generated them, already exists in the law enforcement community.[21] Authentication of data and demonstrating the integrity of data, samples and systems is critical in forensic science and is well studied. The SAB has recommended that the OPCW should continue to strengthen its working relationships with sources of such expertise.

2.5 DIGITIZATION OF INVESTIGATION SITES

Digitization of an investigation site provides an exact record of the scene at a specific moment in time. Remote sensing tools and methods, such as photogrammetry and laser scanning, can provide real-time two- or three-dimensional images of an investigation site prior to entry and during an investigation. They can also allow investigators to compare past images with images taken more recently to ascertain changes that may have taken place since the initial documentation. These methods can enhance the speed and accuracy of data collection from a scene, as the digitalized records can continue to be examined after the investigation team has left (including by using virtual reality tools).

Digital devices can track the handling and integrity (chain of custody) of collected samples. The effectiveness of these devices can be enhanced using combinations of tracking devices, such as the Trace Identification Number (Spoor Identificatie Nummer, SIN)[22] and the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) On-Site Inspection sample-tracking system.[23]

[21] E. Casey and T.R. Souvignet, "Digital Transformation Risk Management in Forensic Science Laboratories", Forensic Science International, vol. 316, November 2020, https://doi.org/10.1016/j.forsciint.2020.110486; Organization of Scientific Area Committees for Forensic Science (OSAC) Task Group on Digital/Multimedia Science, A Framework for Harmonizing Forensic Science Practices and Digital/Multimedia Evidence, OSAC, February 2019, https://www.nist.gov/system/files/documents/2018/01/10/osac_ts_0002.pdf; E. Casey, "Reconstructing Digital Evidence", in W.J. Chisum and B.E. Turvey, Crime Reconstruction, 2nd edition, Elsevier, 2011, pp. 531–548, https://doi.org/10.1016/b978-0-12-386460-4.00017-5; and E. Casey et al., "The Growing Impact of Full Disk Encryption on Digital Forensics", Digital Investigation, vol. 8, no. 2, November 2011, pp. 129–134, https://doi.org/10.1016/j.diin.2011.09.005.

[22] For additional information see Polytrack, https://polytrack.nl/.

[23] X. He and X. Ge, "T3.3-P11 Several Key COTS Equipments' Potential Application to CTBTO OSI", CTBT Science and Technology 2019 Conference, 24–28 June 2019, https://ctnw.ctbto.org/ctnw/abstract/32290.

2.6 WIDER REQUIREMENTS

OPCW procedures have been developed for circumstances that are generally well defined and predictable. However, for non-routine missions the parameters for on-site activity are often impossible to predict in advance and may be highly constrained. Inspectors may have little time to prepare for a visit to a site, they may have only a short time on-site, and the type or quantity of equipment they can bring to it may be very limited.[24]

In such situations it is important to obtain as much information as possible in advance of a visit, to have a capability to extract the maximum amount of information from the site quickly, and to have equipment that is simple, versatile, and easy to transport and use. Access to technical experts during mission planning and operation can maximize the opportunity to identify key remote sensing technologies to support a mission. In many cases, there are agencies with well-established capabilities that can support a mission, for instance the United Nations Institute for Training and Research (UNITAR) in the case of satellite imagery.[25] However, there needs to be a clear understanding of the types of information that can be accessed and the agencies with the expertise to provide appropriate interpretation. For example, the world is imaged daily, and high-resolution imagery data is available from open and commercial sources. But interpretation of such a data set requires specialist capabilities that need to be targeted to the user's requirements. This is also the case for the on-site acquisition and interpretation of high-resolution three-dimensional data. These types of capability could be facilitated through service-level agreements or memoranda of understanding with those agencies. Training for the OPCW Technical Secretariat and joint exercise programmes with technology partners would support the introduction of new remote sensing capabilities to enhance current procedures.

The OPCW should systematically monitor technical developments and consider how they could be used to further strengthen its verification capabilities. Priority should be given to tools that will allow rapid and efficient on-site information gathering, which would provide the greatest amount of information in time-constrained and potentially non-permissive operating environments. Nevertheless, it is crucial to validate new remote sensing approaches before they are implemented, together with the methods for the secure transfer of information and cybersecurity. The SAB will continue to provide information on technologies of potential value in its reports,[26] and it has proposed that the OPCW conduct a modest technology evaluation and adaptation programme, financed through its budget. Individual CWC States parties could supplement this effort through a systematic technical support programme to meet the

[24] OPCW, "Report of the Scientific Advisory Board's Workshop on Emerging Technologies", SAB-26/WP.1, 21 July 2017, paragraphs 5.3–5.5, https://www.opcw.org/sites/default/files/documents/SAB/en/sab26wp01_SAB.pdf. See also OPCW, "Summary of the First Meeting of the Scientific Advisory Board's Temporary Working Group on Investigative Science and Technology", SAB-27/WP.1, 26 February 2018, https://www.opcw.org/sites/default/files/documents/SAB/en/sab-27-wp01_e_.pdf.

[25] See United Nations Institute for Training and Research, http://www.unitar.org/.

[26] OPCW, Verification, Report of the Scientific Advisory Board's Temporary Working Group, SAB/REP/1/15, June 2015, https://www.opcw.org/sites/default/files/documents/SAB/en/Final_Report_of_SAB_TWG_on_Verification_-_as_presented_to_SAB.pdf; OPCW, "Report of the Scientific Advisory Board's Workshop on Emerging Technologies", SAB-26/WP.1, 21 July 2017, https://www.opcw.org/sites/default/files/documents/SAB/en/sab26wp01_SAB.pdf; and OPCW, "Report of the Scientific Advisory Board on Developments in Science and Technology for the Fourth Special Session of the Conference of the States Parties to Review the Operation of the Chemical Weapons Convention", RC-4/DG.1, 30 April 2018, https://www.opcw.org/sites/default/files/documents/CSP/RC-4/en/rc4dg01_e_.pdf. An executive summary is also available from https://www.opcw.org/sites/default/files/documents/2018/10/SAB_RC4-Executive_Summary_Recommendations_-_web.pdf.

requirements defined by the OPCW. Such a function would usefully include field evaluation in relevant training scenarios. The technology support programme that has been conducted by the International Atomic Energy Agency (IAEA) and its member States provides a relevant international model.[27]

2.7 REFLECTIONS

The views expressed in this essay reflect recommendations, endorsed by the SAB, from the findings of the TWG on Investigative Science and Technology. The Director-General and the OPCW will ultimately determine how (and if) these and other recommendations are to be addressed in their review of the TWG's end-of-mandate report.

It is not assumed that all CWC States parties will support adoption of every recommendation. Nevertheless, digital transformation is clearly under way (and further discussed in the fifth essay of this report), and with it come new capabilities and approaches for overcoming verification challenges through the integration of remote sensing and data collection. Fully reaping the benefits that are provided by such new capabilities and approaches requires that verification needs to be looked at in new ways. While this is sure to spark debate, such discourse embraces the spirit of the Chemical Weapons Convention, which specifies in paragraph 6 of Article VIII, that "In undertaking its verification activities the Organization shall consider measures to make use of advances in science and technology".[28]

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[27] IAEA, Research and Development Plan: Enhancing Capabilities for Nuclear Verification, IAEA Safeguards, STR-385, January 2018, https://www.bnl.gov/ISPO/docs/STR-385-IAEA-Department-of-Safeguards-RD-Plan.pdf; and IAEA, Development and Implementation Support Programme for Nuclear Verification 2018–2019, IAEA Safeguards, STR-386, January 2018, https://www.iaea.org/sites/default/files/18/09/sg-str-386-development-support-programme.pdf. Notably, the IAEA has also used crowdsourcing approaches to gain access to new capabilities. See e.g. M. Dubertrand, "Robotics in Nuclear Verification: Sparking Innovation Through Crowdsourcing", IAEA, 19 September 2018, https://www.iaea.org/newscenter/news/robotics-in-nuclear-verification-sparking-innovation-through-crowdsourcing.

[28] Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on Their Destruction, 1997, Article VIII(6), https://www.opcw.org/chemical-weapons-convention/articles/article-viii-organization.

3 EMERGING TRENDS IN COMMERCIAL REMOTE SENSING FOR NUCLEAR ARMS CONTROL

In contrast to the Cold War – when only a few powerful States, including the Soviet Union and the United States of America, were able to observe the earth from space – private companies, universities and consortia are currently joining the remote sensing boom, along with many more governments. Today, hundreds of commercial satellites have been launched into space for the purpose of earth observation.[29] Looking at an image of part of the Earth on your smartphone while you search for directions is second nature to many in this digital age, and remote sensing is no longer primarily synonymous with espionage. This essay considers the implications of commercial remote space-based sensing for nuclear arms control, which while gaining prominence in the International Atomic Energy Agency (IAEA) as a tool for Safeguards, still remains underutilized in other agreements.

FIGURE 1 *Fusion of remote sensing with other forms of data*

[29] Union of Concerned Scientists (UCS), "UCS Satellite Database", 1 August 2020, https://www.ucsusa.org/resources/satellite-database.

More companies and countries are getting involved in earth observation, which means no single State has a monopoly on the data. This also makes it harder for any one State to effectively control the publication of data on a specific area of its territory through national legislation.[30] In July 2020, the US rolled back a previous law that restricted US-based satellite companies to distributing 2m resolution imagery of Israeli-controlled territory, explicitly pointing to the number of non-US-based satellite companies already sharing 0.4m resolution imagery. Multiple sensors controlled by multiple States raises confidence in what is being recorded from space. Space-based sensors offer the benefit of side-stepping claims of sovereignty, and non-classified data makes information more shareable, which levels the playing field.

Civilian analysts are forming international networks, codes of behaviour and toolkits for the common purpose of making the world safer.[31] This organic crowdsourcing activity means that more eyes are looking at remote sensing data, and a greater diversity of knowledge and experience can potentially be brought to bear on it. Local knowledge and technical expertise are combined in near real time using social media platforms like Twitter, Slack and WhatsApp to fuse remote sensing data with other data such as photos, videos, social media, trade flows and more (see Figure 1).

3.1 ADVANCES IN COMMERCIAL REMOTE SENSING

The democratization of remote sensing is in itself a significant technical achievement; it permits broad coverage of the Earth's surface and provides a diversity of sources and tools for government and civil society alike. Because there are now more sensors and more types of sensor covering every part of the planet, new tools in machine learning such as object detection, change detection and novel applications of data science are on the rise. These are not just available to governments, as universities and industry are driving the development and uptake of new technologies.

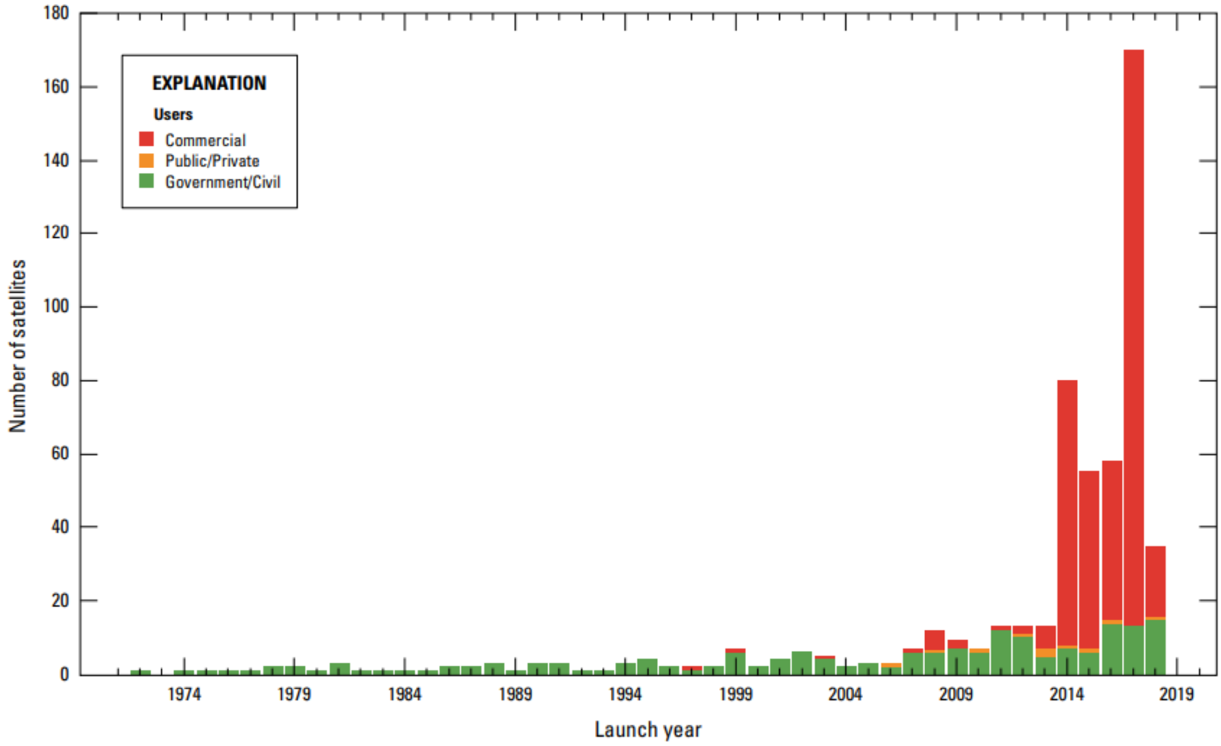
There are more sensors orbiting the Earth than ever before (see Figure 2). In 2018, a United States-based satellite company, Planet, was the first entity to capture images of the entire surface of the Earth every day. This represents a capability that even governments cannot match. Soon, the frequency of fresh imagery generation will be counted in hours instead of days. The cost of hiding illicit activity has already increased dramatically as regular civilians are now making discoveries that only teams inside intelligence services could make years ago. For example, in 2018 Dr. Jeffrey Lewis and his team discovered a possible uranium enrichment site near Kangsonin the Democratic People's Republic of Korea.[32]

30 United States Federal Register, "Notice of Findings Regarding Commercial Availability of Non-U.S. Satellite Imagery With Respect to Israel", 21 July 2020, https://www.federalregister.gov/documents/2020/07/21/2020-15770/notice-of-findings-regarding-commercial-availability-of-non-us-satellite-imagery-with-respect-to.

31 Stanley Center, "The Grey Spectrum: Ethical Decision Making with Geospatial and Open-source Analysis", January 2020, https://stanleycenter.org/publications/the-gray-spectrum/. See also the community and tools provided by Datayo, https://datayo.org/ and Open Nuclear Network: https://oneearthfuture.org/program/open-nuclear-network/code-of-ethics.

32 A. Panda. "Exclusive: Revealing Kangson, North Korea's First Covert Uranium Enrichment Site", 13 July 2018, The Diplomat, https://thediplomat.com/2018/07/exclusive-revealing-kangson-north-koreas-first-covert-uranium-enrichment-site/.

FIGURE 2 Satellite launches by year.[33]



Multispectral[34] and even hyperspectral[35] sensors are being developed that are more promising than previous technology that used only three or four bands of light. For example, MAXAR's WorldView-3 imagery has 29 spectral bands.[36] When these multispectral bands are combined in different ways, they can reveal information about natural and human impacts on vegetation, soil, fires, water and ice as well as arms control related topics such as camouflage and signature of nuclear facility activity. More applications of this type are discovered every year. Many of the spectral bands also help in land classification and can provide data to improve the accuracy of measurements taken from space through atmospheric correction.

Hyperspectral data takes this principle even further. Hyperspectral sensors can collect hundreds of bands in narrower slices, essentially performing spectroscopy of the Earth's surface. (Spectroscopy is the study of the absorption and emission of light and other radiation

[33] J.B. Christopherson. S.N. Ramaseri Chandra and J.Q. Quanbeck, 2019 Joint Agency Commercial Imagery Evaluation—Land Remote Sensing Satellite Compendium, United States Geological Survey, 2019, https://pubs.usgs.gov/circ/1455/cir1455.pdf.

[34] Multispectral data is collected by sensors that measure reflected electromagnetic energy in pre-defined "bands" as defined by each satellite or aerial provider. Multispectral sensors usually have 3–12 different band measurements in the visible and non-visible spectrum of light for each pixel of the images they produce. Most consumers are used to seeing data reflected in the green-, blue- and red (GBR)- wavelengths of light, however mixing other bands within the near-infrared, short-wave infrared and thermal-infrared ranges reveals more information than would been seen by the human eye.

[35] Hyperspectral data is collected by sensors that measure reflected electromagnetic energy in dozens or hundreds of pre-defined "bands". Because these bands tend to be narrower and more numerous, they can be compared to spectroscopy. There is a lot of excitement around identifying chemical substances on the surface of the Earth to improve agricultural yields and identify mineral deposits, as well as other commercial applications. This capability is still emerging in space due to the high volume of data that needs to be transmitted to Earth.

[36] Bands are artificial "slices" of the electromagnetic spectrum. For example, Maxar's WorldView-3 sensor defines the visible red band as light reflecting with wavelengths of 626–696 nanometres. DigitalGlobe, "Spectral Response for DigitalGlobe Earth Imaging Instruments", https://wp-cdn.apollomapping.com/web_assets/user_uploads/2014/10/14123451/Spectral_Response_for_DigitalGlobe_Earth_Imaging_Instruments_102214.pdf.

from matter to perform analysis.) In 2019, the German space agency, the Deutsches Zentrum für Luft- und Raumfahrt (DLR), and Teledyne Brown joined forces to put the DLR Earth Sensing Imaging Spectrometer (DESIS) on the International Space Station. With 235 spectral bands, DESIS can identify the spectral "fingerprint" of materials. While applications to arms control have not been widely researched since its operation, DESIS and sensors like it will be able to provide a chemical analysis of materials on the ground and monitor changes. DESIS can already identify rare earths, for example.

Synthetic Aperture Radar (SAR) is quickly moving from the military to the commercial sphere. Unlike electro-optical imagery, radar is transmitted from space, bounces off the surface of the earth and is collected again. This "active" sensor does not depend on sunlight, meaning treaty monitoring can occur at night and can penetrate clouds. Airbus's TerraSAR-X satellite offers 24-centimetre spatial resolution SAR and has a range of applications including tracking vessels at sea. It was even able to identify the Democratic People's Republic of Korea's space launch vehicle while it was covered by a fiberglass roof.[37]

Coherent change detection using SAR by Airbus showed the intensity of patrolling around the uranium-enrichment facility at Qom, Islamic Republic of Iran, in 2010, and pairing SAR with height data identified the entrances to its tunnels.[38] A comparison of Mount Mantap before and after the Democratic People's Republic of Korea's most recent nuclear test showed massive earth subsidence, indicating that approximately 34 hectares of the mountain subsided by several metres.[39]

Capella Space is attempting to do with SAR what Planet did with electro-optical imagery: it is creating a constellation of lower-cost satellites that may have lower spatial resolution than Airbus's TerraSAR-X but have far greater frequency of collection.[40] Meanwhile, Vulcan's Skylight product is using machine learning and pairing electro-optical and SAR imagery with positioning data and a database of vessels to identify ships even if they are not transmitting an automatic identification system (AIS) signal. By applying machine learning algorithms to their ever-growing data set (discussed further in section 5), this company can identify suspicious vessel activity (e.g. ship-to-ship transfers) and also begin to forecast vessel movements.[41] Another innovative company is Hawkeye 360, which uses sensors to trilaterate[42] radio frequencies transmitted between the earth and satellites. These sensors can help to identify emitters such as satellite Wi-Fi routers or satellite phones.[43] This data is particularly useful when ships that are engaged in illicit activity turn their AIS transceivers off.

[37] A. Puccioni, "Penetrating Vision: Radar Imagery Analysis Fills Intelligence Gaps", Jane's Intelligence Review, May 2016; and A. Puccioni, "Leaps and Bounds: North Korean Nuclear Programme Advances", Jane's Intelligence Review, May 2016.

[38] F.R. Hensler, "TerraSAR-X & TanDEM-X: SAR Precision from Space for the Czech Republic", Presentation to GISAT Open Day, Prague, 10 November 2010, http://www.gisat.cz/images/upload/775a_101110-terrasar-x-4-gisat.pdf.

[39] C. Dill et al., "Synthetic Aperture Radar (SAR) Imagery of North Korea's Punggye-ri Nuclear Test Site", Arms Control Wonk, 13 September 2017, https://www.armscontrolwonk.com/archive/1203852/sar-image-of-punggye-ri/.

[40] Capella Space, "Technology", https://www.capellaspace.com/technology/.

[41] Skylight, "Skylight Helps Improve Maritime Transparency to Protect our Oceans", https://vulcan.com/skylight.

[42] Trilateration involves measuring distances of radio frequencies to determine locations.

[43] Hawkeye360, "Technology", https://www.he360.com/technology.

3.2 REFLECTIONS ON OPEN-SOURCE SATELLITE DATA

The boom in open-source satellite data may present wider security concerns for some actors. For example, States may be concerned over how open-source satellite data could aid the nuclear targeting of adversaries; and thus far developments are disproportionately benefiting technologically advanced States with strong academic and industrial bases. Moreover, commercial space-based remote sensing is limited as a standalone tool and it is certainly no replacement for traditional International Atomic Energy Agency (IAEA) Safeguards inspections or even the aerial imaging offered by the 1992 Open Skies Treaty.

Nonetheless, the advancement of remote sensing and its convergence with other technological trends, including machine learning and big data, presents several significant opportunities to enhance arms control and disarmament measures and augment existing treaty verification and monitoring capabilities. These tools can offer sound, verifiable evidence that make inspectors more productive. Moreover, the data is shareable due to its open-source commercial nature, meaning that many – not just those with their own military intelligence capabilities – can participate in arms control. To ensure this trend continues, States must invest in resources that develop human capacity and technology fairly through their promotion in international organizations and subsidize the cost of imagery purchases for arms control and treaty verification.

In future, the further application of machine learning tools could further improve analysis of satellite data. However, human expertise will nonetheless remain essential. This entails building capacity to collect, process and analyse satellite data across a more diverse range of countries. Moreover, to be effective, it will be important that the chain of custody of such data is carefully documented and protected from tampering to ensure clarity and "the ability to retrace all processing steps that an image undergoes from the satellite to those used by analyst[s]".[44] This may further require that satellite data providers share details on calibration of their satellite systems as well as the methods they employed in processing data.[45]

[44] T. Patton et al., Emerging Satellites for Non-Proliferation and Disarmament Verification, Vienna Center for Disarmament and Non-Proliferation, January 2016, p. 20, http://nonproliferation.org/vcdnp/wp-content/uploads/2016/06/160614_copernicus_project_report.pdf.

[45] The development of ISO standards is useful here. For example, ISO 19130 "presents imagery sensor models for geo-positioning, where the model is applied to sensor data". T. Patton et al., Emerging Satellites for Non-Proliferation and Disarmament Verification, Vienna Center for Disarmament and Non-Proliferation, January 2016, pp. 8–9, http://nonproliferation.org/vcdnp/wp-content/uploads/2016/06/160614_copernicus_project_report.pdf.

4 USING OPEN-SOURCE TRADE DATA TO MONITOR TRADE IN BIOWEAPONS RELEVANT ITEMS

In addition to remote sensing and open-source satellite data, the development of online, publicly accessible databases present further opportunities for the reliable collection of other kinds of data. Many readers might use open-source data on the movement of goods and people on a routine basis without even thinking of it. Examples include checking traffic before choosing a route and determining the arrival time of public transport at a given location. Similar data is used for commercial purposes, for instance in fleet or harbour management: in addition to its real-time function, such data is often collected in databases on past activities. Non-governmental organizations using open sources have demonstrated that a broad variety of data can be combined and used in support of monitoring or assessing compliance with WMD treaties. Monitoring of trade data could play an additional role. The concept explained here addresses databases that record export and import data derived from customs authorities.

In the past, trade data has proven valuable in informing assessments of non-compliance with the biological weapons regime. For example, in the early 1990s, trade data – specifically a spike in imported biological culture media – provided the United Nations Special Commission (UNSCOM) with an early indicator of Iraq's biological weapons programme.[46] This was before it became possible to extract data from the online databases that are now available to the public. In combination with other methods, this kind of pattern recognition can be useful in detecting anomalies and possible signs of non-compliance.

4.1 OPEN-SOURCE TRADE DATA

Items that are legitimately traded across national borders are typically recorded separately by the importing and exporting customs authorities.[47] The data sets that derive from these records are stored with the financial administrations of the respective states involved. In addition, this data is also forwarded to international databases (e.g. the United Nations Comtrade Database[48]) in accordance with States' legal obligations under Article 3 of the 1983 International Convention on the Harmonized Commodity Description and Coding System (HS Convention). Data from these databases can be accessed, downloaded and analysed by anyone at no cost.

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46 E.g. UN Security Council, "Status of Verification of Iraq's Biological Warfare Programme", Appendix III of Security Council, S/1999/94, 29 January 1999, https://undocs.org/S/1999/94. See also G.S. Pearson, "The UNSCOM Saga: Chemical and Biological Weapons Non-proliferation", Palgrave Macmillan, 1999, p. 212, https://doi.org/10.1057/9780230596900.

47 Analysts shall bear in mind that re-exports and imports might complicate some cases, but do not generally preclude an evaluation.

48 UN Trade Statistics, "Harmonized Commodity Description and Coding Systems (HS)", 2017, https://unstats.un.org/unsd/tradekb/Knowledgebase/50018/Harmonized-Commodity-Description-and-Coding-Systems-HS; and UN Comtrade database, https://comtrade.un.org/db/.

Traders submitting customs declarations for entry into international databases use the Harmonized System (HS) code allocated by the World Customs Organization (WCO).[49] This is a globally compatible 6-digit code that is allocated to all traded items.[50] These codes cover more than a million different tradable items.

Currently, the coverage of HS codes in the biological domain lacks adequate detail. The lists developed by UNSCOM and subsequently the United Nations Monitoring, Verification and Inspection Commission (UNMOVIC) to identify possible biological weapons programmes contain approximately 40 items; only one of these items has an individual number ("prepared culture media for development of microorganisms" under HS code 382100). As such, it is not yet possible to extract data on the international trade in a wider range of dual-use items, such as fermenters or drying equipment.

Moreover, there are also limits to the quality of the data. Recorded data obviously omits smuggled goods and materials or other forms of hidden trade. Frequently there are also discrepancies in the recording of trade data: export and import data rarely match perfectly, variously due to differences in valuations of imports and exports or "differences in inclusions/exclusions of particular commodities".[51] Furthermore, trade data provides scant insight into the indigenous production of materials and equipment.[52]

Despite these limitations, the data available is usually sufficient to get an idea about trade flow patterns over time as well as anomalous increases in certain imports. As noted above, for UNSCOM inspectors the growth in consumption of imported culture media (from 0.5 tons to 40 tons) was one of the first hints pointing toward the early Iraqi biological weapons programme.[53] For UNSCOM this data was not available from publicly accessible online databases. However, today, it is possible to analyse trade in items using the online database and to detect discrepancies or unexpected peaks in certain trade patterns. For example, should an observer detect a remarkable peak in trade of certain biological materials, such as culture media, this, in combination with other information, could help inform assessments of compliance.

[49] Relevant links to the HS codes, the descriptions with the HS codes in different formats and the correlation table with the HS amendments since 1996 can be found at UN Trade Statistics, "Harmonized Commodity Description and Coding Systems (HS)", 2017, https://unstats.un.org/unsd/tradekb/Knowledgebase/50018/Harmonized-Commodity-Description-and-Coding-Systems-HS; and and UN Comtrade database, https://comtrade.un.org/db/.

[50] The HS code should not be confused with the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) or "UN numbers".

[51] See UN Comtrade, "Disclaimer on Coverage and Limitations", 2016, https://comtrade.un.org/db/help/uReadMeFirst.aspx.

[52] G. Jeremias and M. Himmel, "Can Everyone Help Verify the Bioweapons Convention? Perhaps, via Open-Source Monitoring", Bulletin of the Atomic Scientists, vol. 72, no. 6, 2016, pp. 412–417, https://doi.org/10.1080/00963402.2016.1240487.

[53] G. Jeremias, and J. van Aken, "Harnessing Global Trade Data for Biological Arms Control", Nonproliferation Review, vol. 13, no. 2, 2006, pp. 189–209, https://doi.org/10.1080/10736700601012037.

4.2 REFLECTIONS: MANAGING EXPECTATIONS

Proponents of open-source data need to manage expectations about what this method can contribute. First, indicators of compliance or non-compliance extracted from open-source trade data will be context dependent and non-scalable. In other words, indicators of activities that suggest possible non-compliance in a country with a limited biotechnology infrastructure will be different to those indicators that would apply to countries with large-scale bio-pharmaceutical research and development programmes. Second, open-source tools need to be used in corroboration with other methods to collect evidence in order to draw conclusions about compliance. Trade data indicators are of no value on their own.

Third, at present the Harmonized System goes into little detail in its coverage of dual-use biological items. However, the detail of data on biological items could be improved in the future as the allocation of individual 6-digit codes to relevant items in the HS system is amended every five years. In the past, the WCO has developed and amended HS codes in cooperation with other international organizations, including those related to disarmament such as the OPCW,[54] although not primarily for verification purposes.

There have been comparable attempts to enhance transparency in the biological field through the adoption of individual codes for dual-use biological items. These were developed as early as 2007 by the WCO's Harmonized System Review Sub-Committee in cooperation with Hamburg University.[55] States parties to the HS Convention rejected this 2007 initiative and another one in 2013 for reasons that remain unclear. However, any BWC State party that is also a member of the WCO could resume work on the implementation of the codes in the current HS amendment cycle. For that matter, so too could the BWC Implementation Support Unit, for instance if it were to be given a mandate by the ninth BWC Review Conference, in 2021. Such a process could be augmented through convergence with technical developments in other areas, such as machine learning (as discussed in section 5). This could be complemented by available open-source carrier data pertaining to shippers and consignees, for example.

Notably, there has already been some consideration of the role of machine learning tools in detecting miscalculations and under-valuations of traded goods.[56] Additionally, scholars have begun to explore machine learning's potential to classify images of specific items of equipment on export control lists.[57] Further consideration of how machine learning could be applied to detect anomalies from a proliferation perspective or to better understand emerging trends in biotechnology may produce valuable applications in compliance and enforcement in the biological weapons regime.

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[54] Indeed, in 2017 the WCO and the OPCW signed a memorandum of understanding that expands their cooperation to tighten national and international controls on the trade in toxic chemicals. WCO, "WCO and OPCW Expand Cooperation to Prevent Misuse of Toxic Chemicals", 16 January 2017, http://www.wcoomd.org/en/media/newsroom/2017/january/wco-and-opcw-expand-cooperation-to-prevent-misuse-of-toxic-chemicals.aspx.

[55] For further information see Research Group for Biological Arms Control, "Trade Monitoring for Biological Dual Use Items", 2013, http://biological-arms-control.org/projects_trademonitoring.html.

[56] M. Squirrell, "How Machine Learning Can Automate the Determination of the Valuation of Goods", WCO News, February 2020, https://mag.wcoomd.org/magazine/wco-news-91-february-2020/how-machine-learning-can-automate-the-determination-of-the-valuation-of-goods/.

[57] J. Withorne, Machine Learning Applications in Nonproliferation: Assessing Algorithmic Tools for Strengthening Strategic Trade Controls, NonPro Notes, James Martin Center for Nonproliferation Studies, 4 August 2020, https://www.nonproliferation.org/wp-content/uploads/2020/08/CNS_Nonpro_Notes_082020.pdf.

5 ARTIFICIAL INTELLIGENCE, DIGITIZATION AND VERIFICATION

Digitization is the integration of information technologies, data analytics, data-collection capabilities and digitized data. Digitization has steadily expanded its reach for more than 25 years,[58] and is now an integral part of business and operations across a multitude of sectors and applications.[59] Driven by artificial intelligence (AI), digitization has enabled new tools for research, innovation and business that have transformed the way in which we work across technical and non-technical disciplines alike ("digital transformation").[60] The AI that powers these tools is both dynamic and constantly evolving.[61] Its adoption continues to grow.

In a security context, AI discussions often focus on challenges, vulnerabilities and risks,[62] including those related to AI and chemical and biological weapons.[63] These complex security concerns cannot be ignored. However, digitization is not an isolated phenomenon that we simply watch from afar and try to assess what its impact will be – it has become ubiquitous. This challenges us to also consider opportunities and benefits, including for applications in disarmament and non-proliferation. This view is enshrined in the Chemical Weapons Convention (CWC): "In undertaking its verification activities the [Organisation for the Prohibition of Chemical Weapons (OPCW)] shall consider measures to make use of advances in science and technology".[64] The OPCW's Scientific Advisory Board (SAB) has also expressed

58 J. Bughin, J. Manyika and T. Catlin, "Twenty-Five Years of Digitization: Ten Insights into How to Play It Right", McKinsey Global Institute, 21 May 2019, https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/twenty-five-years-of-digitization-ten-insights-into-how-to-play-it-right.

59 S. Buchholz and B. Briggs, "Tech Trends 2020", Deloitte Insights, 15 January 2020, https://www2.deloitte.com/us/en/insights/focus/tech-trends/2020/tech-trends-introduction.html; and S. Buchholz and B. Briggs, "Executive Summary: Tech Trends 2019", Deloitte Insights, 16 January 2019, https://www2.deloitte.com/us/en/insights/focus/tech-trends/2019/executive-summary.html.

60 Organisation for Economic Co-operation and Development (OECD), The Digitalisation of Science, Technology and Innovation: Key Developments and Policies, 2020, https://doi.org/10.1787/b9e4a2c0-en.

61 N. Benaich and I. Hogarth, "State of AI Report 2019", 2019, https://www.stateof.ai/2019. See also R. Steelberg, "The State of Artificial Intelligence in 2020: AI by the Numbers", Veritone, 10 January 2020, https://www.veritone.com/blog/the-state-of-artificial-intelligence-in-2020-ai-by-the-numbers; Appen, "The State of AI and Machine Learning", 2020, https://appen.com/whitepapers/the-state-of-ai-and-machine-learning-report/.

62 E.g. Stanley Center for Peace and Security, UNODA and Stimson Center, "The Militarization of Artificial Intelligence", August 2019, https://www.stimson.org/2020/the-militarization-of-artificial-intelligence/; and B. Cheatham, K. Javanmardian and H. Samandari, "Confronting the Risks of Artificial Intelligence", McKinsey Quarterly, 26 April 2019, pp.1–9, https://www.mckinsey.com/business-functions/mckinsey-analytics/our-insights/confronting-the-risks-of-artificial-intelligence.

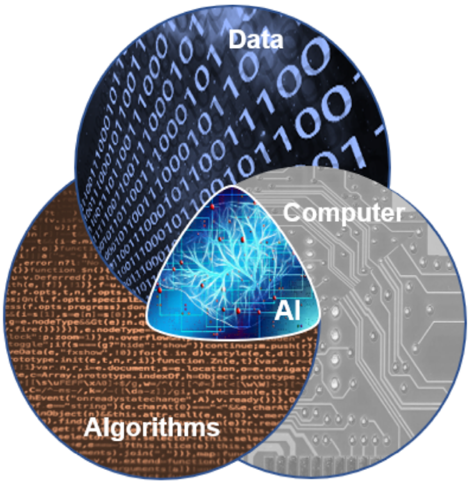
63 M.B. Hamby, "New Technology Makes Production of WMD's Easier, MIIS Experts Warn", Middlebury Institute of International Studies (MIIS), October 2019, https://www.middlebury.edu/institute/news/new-technology-makes-production-wmds-easier-miis-experts-warn; K. Brockmann, S. Bauer and V. Boulanin, Bio Plus X: Arms Control and the Convergence of Biology and Emerging Technologies, Stockholm International Peace Research Institute, March 2019, https://www.sipri.org/publications/2019/other-publications/bio-plus-x-arms-control-and-convergence-biology-and-emerging-technologies. SIPRI has also produced a study on AI in relation to nuclear weapons. V. Boulanin et al., Artificial Intelligence, Strategic Stability and Nuclear Risk, Stockholm International Peace Research Institute, June 2020, https://www.sipri.org/publications/2020/other-publications/artificial-intelligence-strategic-stability-and-nuclear-risk.

64 Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on Their Destruction, 1997, Article VIII(6), https://www.opcw.org/chemical-weapons-convention/articles/article-viii-organization.

this view in its recommendations.[65]

This essay looks at some of the opportunities that digitization and AI (with an emphasis on machine learning) might provide for CWC verification activities.

FIGURE 3 *An illustration of the artificial intelligence triad*[66]



5.1 ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

When considering how AI could benefit (as well as challenge) the implementation of a disarmament and non-proliferation treaty, it must be appreciated that AI is an imprecise term. AI is commonly used to describe software systems that possess "general" or "general-purpose" intelligence,[67] which evokes images of intelligent machines and debate on what is truly possible to achieve.[68] At the same time, the term AI is also used to describe software techniques (algorithms) that instruct computers to perform tasks and solve problems traditionally thought to require human intelligence. Through the integration of multiple algorithms, the computer becomes capable of performing more complex tasks that can process a broader range of inputs and initiate actions in response. To make the AI system functional requires both the algorithm and the computer, along with a third component: data. This can be thought of as an "AI Triad" (see Figure 3), in which the three components are integrated together and depend on one another.[69] On their own, however, these three components can only perform computational tasks. In order to produce a device that can perform other functions (including collecting data), additional devices and technologies must be integrated into the system. These other components might include cameras and sensors to collect information to analyse (and allow the computational tools to make decisions); machines (robots or vehicles) to pilot;

[65] OPCW, "Report of the Scientific Advisory Board on Developments in Science and Technology for the Fourth Special Session of the Conference of the States Parties to Review the Operation of the Chemical Weapons Convention", RC-4/DG.1, 30 April 2018, https://www.opcw.org/sites/default/files/documents/CSP/RC-4/en/rc4dg01_e_.pdf, paragraph 18 and Annex I, paragraphs 69–75.

[66] B. Buchanan, The AI Triad and What It Means for National Security Strategy, Center for Security and Emerging Technology (CSET), August 2020, https://cset.georgetown.edu/wp-content/uploads/CSET-AI-Triad-Report.pdf.

[67] F. Berruti, P. Nel and R. Whiteman, "An Executive Primer on Artificial General Intelligence", 29 April 2020, McKinsey Insights, https://www.mckinsey.com/business-functions/operations/our-insights/an-executive-primer-on-artificial-general-intelligence.

[68] R. Fjelland, "Why General Artificial Intelligence Will Not be Realized", Humanities and Social Sciences Communications, vol. 7, no. 1, 2020, article 10, https://www.nature.com/articles/s41599-020-0494-4.

[69] B. Buchanan, The AI Triad and What It Means for National Security Strategy, Center for Security and Emerging Technology (CSET), August 2020, https://cset.georgetown.edu/wp-content/uploads/CSET-AI-Triad-Report.pdf.

and tools that convey information to humans or the AI components of other systems. As a result, AI is a multitude of techniques, approaches and functions rather than any single, specific technological device.[70] This essay looks at AI in the context of its role within a system of integrated components designed to have capabilities relevant to CWC verification.

Machine learning is one of the many techniques that falls under the umbrella of AI. It describes algorithms that allow machines to learn from data, eliminating the need for human instruction to perform certain tasks.[71] Machine learning algorithms are trained, using training data, to identify patterns. This "knowledge" is then applied to analyse or interpret new data.67

Machine learning itself is not a single technique. Rather it is a toolkit of algorithms that are commonly thought of as belonging to three broadly defined categories: supervised learning, unsupervised learning and reinforcement learning (see Table 1).[72] Within each category of machine learning, there can be found a diversity of approaches, algorithms, models and applications. The three categories describe the way the algorithms are designed to function, not the actual computer code that underpins them.[73]

[70] World Intellectual Property Organization (WIPO), WIPO Technology Trends 2019: Artificial Intelligence, 2019, https://www.wipo.int/publications/en/details.jsp?id=4386.

[71] B. Buchanan and T. Miller, Machine Learning for Policymakers: What It is and Why It Matters, Belfer Center for Science and International Affairs, June 2017, https://www.belfercenter.org/sites/default/files/files/publication/MachineLearningforPolicymakers.pdf; and D. Pickell, "The Complete Guide to Machine Learning in 2020", G2 Learning Hub, 24 June 2019, https://learn.g2.com/machine-learning.

[72] Ibid.

[73] World Intellectual Property Organization (WIPO), WIPO Technology Trends 2019: Artificial Intelligence, 2019, https://www.wipo.int/publications/en/details.jsp?id=4386.

TABLE 1 Broad categories of machine learning[74]

Supervised learning	Supervised learning is the most frequently used approach to machine learning, providing an algorithm that can make predictions based on the data sets with which it was trained. In a simple application, these types of algorithm might be used to perform a binary classification task such as labelling an email as "spam" or "not spam". A more complex application could be the identification of specific categories of chemicals based on analysis of a molecular structure.
Unsupervised learning	In unsupervised learning, algorithms are designed to recognize patterns in data and to group data or observations into clusters of similarity, or to recognize unusual (outlier) observations within a data set. An application of this approach might be in market research to identify different groups of consumers.
Reinforcement learning	Reinforcement learning is used to train software to complete tasks correctly through indicating whether the outcome obtained by an action of the software had a positive or negative result; this technique finds use in gaming and robotics. For gaming, the algorithm is taught the basic moves and action of the game, and then it is allowed to play the game and learn how the moves and actions taken lead to wins or losses. After a sufficient number of games are played, the algorithm would be expected to have learned to always play a "perfect game".

As fantastic or scary as the capabilities of AI may seem (depending on one's perspective), AI systems often have limited versatility as they are typically designed to perform very specific tasks.[75] Sometimes, the algorithms do not always function as intended, this might be expected when training data sets differ significantly from the cases to which it is subsequently applied, or if it encounters an unfamiliar situation.[76] Abrupt changes in the types of data that the algorithms collect and analyse can also confuse the system.[77] This can raise questions about how much trust should be placed in these systems, and what is required to develop more reliable and accurate AI.

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74 Source: B. Buchanan and T. Miller, Machine Learning for Policymakers: What It is and Why It Matters, Belfer Center for Science and International Affairs, June 2017, https://www.belfercenter.org/sites/default/files/files/publication/MachineLearningforPolicymakers.pdf; and D. Pickell, "The Complete Guide to Machine Learning in 2020", G2 Learning Hub, 24 June 2019, https://learn.g2.com/machine-learning .

75 B. Bergstein, "What AI Still Can't Do", 19 February 2020, MIT Technology Review, https://www.technologyreview.com/2020/02/19/868178/what-ai-still-cant-do/.

76 W.D. Heaven, "Google's Medical AI was Super Accurate in a Lab. Real Life was a Different Story", 27 April 2020, MIT Technology Review, https://www.technologyreview.com/2020/04/27/1000658/google-medical-ai-accurate-lab-real-life-clinic-covid-diabetes-retina-disease/.

77 E.g. online shopping-related and stock market investment-related algorithms have been confused by abrupt changes in behaviours resulting from actions taken to contain the spread of COVID-19. This demonstrates that even AI tools can be affected by pandemics. See W.D. Heaven, "Our weird behavior during the pandemic is messing with AI models", 11 May 2020, MIT Technology Review, https://www.technologyreview.com/2020/05/11/1001563/covid-pandemic-broken-ai-machine-learning-amazon-retail-fraud-humans-in-the-loop/; and W. Knight, "Even the Best AI Models Are No Match for the Coronavirus" 19 July 2020, Wired, https://www.wired.com/story/best-ai-models-no-match-coronavirus/.

5.2 DIGITIZATION AND INDUSTRY VERIFICATION UNDER THE CHEMICAL WEAPONS CONVENTION

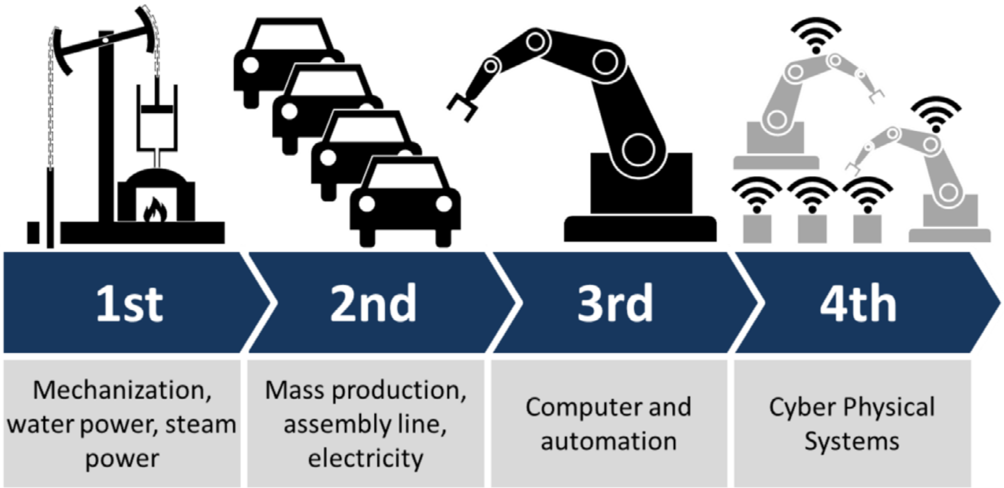
The chemical industry is making significant investment in digitization through the adoption of "Industry 4.0" – a fourth wave of industrial transformation (see Figure 4) that is also being realised in other economic sectors. This moves chemical production into smart factories, integrated cyber-physical information systems and robotics. An industrial Internet of things (IoT) collects and tracks information in real time, allowing the visualization of interactions across supply chains, production processes, sales and customer support. Machine learning (and other forms of AI) combined with sensors, robotics and data streams from across a company enable real-time decision-making across all aspects of the chemical enterprise. The benefits of Industry 4.0 include improved operational efficiency, digitally enabled product offerings, accelerated innovation cycles, intensified collaboration and data sharing, new and more flexible business models, and improved customer interaction.[78]

The chemical industry is also a stakeholder of significance for the implementation of the CWC, through the Convention's industry verification regime.[79] It follows that Industry 4.0 offers an increased ability to track and report information, which has the potential to streamline regulatory reporting and thus CWC declarations. In principle, CWC inspections could then be performed electronically by "sampling and analysis" of data: the production equipment logs would demonstrate the difference between, and the number of types of, processing conditions that had been run on the equipment. This could then be compared for consistency with declared activities. In practice, it is unlikely that CWC States parties (or the companies within those States) could accept this approach, at least for now. However, with the integrated collection of data across the chemical production process, information required for regulatory compliance from all input sources can be more efficiently collected and organized. From this perspective, Industry 4.0 could streamline processes for regulatory reporting and declarations within a State party.

[78] W. Falter et al., Chemistry 4.0: Growth Through Innovation in a Transforming World, Technical report, Deloitte and German Chemical Industry Association, 2017, https://www2.deloitte.com/global/en/pages/consumer-industrial-products/articles/cip-chemistry.html; B. Elser et al., AI & Blockchain: Chemical Industry Insights and Actions, Accenture, 5 June 2019, https://www.accenture.com/us-en/insights/chemicals/ai-blockchain-chemical-industry; S. Lin et al., Shift to Enterprise Grade AI, IBM Institute for Business Value, July 2019, https://www.ibm.com/thought-leadership/institute-business-value/report/chemicals-petroleum-ai; Microsoft, 2019 Manufacturing Trends Report, 2018, https://info.microsoft.com/rs/157-GQE-382/images/EN-US-CNTNT-Report-2019-Manufacturing-Trends.pdf; and World Economic Forum, "Chemistry and Advanced Materials: At the Heart of the Fourth Industrial Revolution", 2020, https://reports.weforum.org/digital-transformation/chemistry-and-advanced-materials-at-the-heart-of-the-fourth-industrial-revolution/.

[79] Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on Their Destruction, 1997, Article VI, https://www.opcw.org/chemical-weapons-convention/articles/article-vi-activities-not-prohibited-under-convention.

FIGURE 4 *Illustration of Industry 4.0*[80]



Meanwhile, there are also signs of digital transformation within the CWC verification regime. This is illustrated by tools that the OPCW has developed for verification purposes including the Secure Information Exchange (SIX)[81] and the Electronic Declaration Information System (EDIS).[82] Adopting digitized approaches beyond submission of declarations has also attracted interest. Many experts recognize the use of distributed ledger technology (blockchains[83]) as a means to reduce the number of discrepancies between the quantities of scheduled chemicals declared by Member States reporting transfers.[84] This is because blockchains can provide a digital record of all transactions of a given chemical product – from its manufacture to its sale to a customer.[85] Notably, there is also interest in applying blockchains for non-proliferation purposes to nuclear materials.[86]

80 Image produced by Christoph Roser at AllAboutLean.com under the free CC-BY-SA 4.0 licence.

81 OPCW, "Secure Information Exchange SIX", https://www.opcw.org/resources/declarations/secure-information-exchange-six.

82 World Economic Forum, "Chemistry and Advanced Materials: At the Heart of the Fourth Industrial Revolution", 2020, https://reports.weforum.org/digital-transformation/chemistry-and-advanced-materials-at-the-heart-of-the-fourth-industrial-revolution/.

83 B. Elser et al., AI & Blockchain: Chemical Industry Insights and Actions, Accenture, 5 June 2019, https://www.accenture.com/us-en/insights/chemicals/ai-blockchain-chemical-industry.

84 OPCW, "Report of the OPCW on the Implementation of the Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on their Destruction in 2018", C-24/4, 28 November 2019, https://www.opcw.org/sites/default/files/documents/2019/12/c2404(e).pdf, paragraphs 1.32–1.33; and United Nations Office for Disarmament Affairs (UNODA), "Side Event on Digital Technologies and Conventional Arms Trade", 25 October 2019, https://www.un.org/disarmament/update/side-event-on-digital-technologies-and-conventional-arms-trade/.

85 L.S. Maxeiner. J.P. Martini and P. Sandner, "Blockchain in the Chemical Industry", Frankfurt School Blockchain Center Working Paper, September 2018, http://explore-ip.com/2018_Blockchain-Chemical-Industry.pdf; and H.E. Pence, "Blockchain: Will Better Data Security Change Chemical Education?", Journal of Chemical Education, vol. 97, no. 7, 14 July 2019, pp. 1815–1818, https://doi.org/10.1021/acs.jchemed.9b00560.

86 Stimson Center, "Blockchain Prototype for Safeguarding Nuclear Material Unveiled & Demonstrated", 10 March 2020, https://www.stimson.org/2020/blockchain-prototype-for-safeguarding-nuclear-material-unveiled-demonstrated/.

5.3 MAKING SENSE OF THE UNIVERSE OF SCHEDULED CHEMICALS

CWC implementation requires that certain chemicals be subject to special verification measures, these are listed in the Convention's three schedules of toxic chemicals and precursors.[87] These schedules list 63 specific chemicals by name and Chemical Abstract Service (CAS) number; other scheduled chemicals are identified through descriptions of families of chemicals based on molecular structure similarities.[88] These families collectively represent untold trillions of possible chemicals,[89] and the 34,254 chemicals listed in the OPCW's Scheduled Chemicals Database cover only a mere fraction of the "chemical space" that the schedules actually encompass.[90]

For chemists who work with scheduled chemicals, the molecular structure criteria that places a given chemical in one of the listed families might be clear when described in atoms and molecules, that is, the "language of chemistry".[91] However, for border or regulatory officials untrained in chemistry, having to look at chemicals as atoms and molecules may not be

[87] Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on Their Destruction, 1997, Annex on Chemicals, https://www.opcw.org/chemical-weapons-convention/annexes/annex-chemicals/annex-chemicals: and updated Schedule 1 as provided in the annex to OPCW, "Guidance for States Parties on Article VI Declaration Obligations and Inspections Following Entry into Force of Changes to Schedule 1 of the Annex on Chemicals to the Chemical Weapons Convention", S/1821/2019/Rev.1, 14 January 2020, https://www.opcw.org/sites/default/files/documents/2020/01/s-1821-2019r1(e).pdf.

[88] Of the 63 specifically listed chemicals, 3 are actually listed because, while they fit under some of the family descriptions, they are granted exemptions from being covered by the CWC schedules.

[89] G. Pontes, et al., "Nomenclature, Chemical Abstracts Service Numbers, Isomer Enumeration, Ring Strain, and Stereochemistry: What Does Any of This Have to Do with an International Chemical Disarmament and Nonproliferation Treaty?", Journal of Chemical Education, vol. 97, no. 7, 14 July 2020, pp. 1715–1730, https://doi.org/10.1021/acs.jchemed.0c00547.

[90] OPCW, "Scheduled Chemicals Database 2019", 2019, https://apps.opcw.org/CAS/default.aspx.

[91] G. Pontes, "What is The Language of Chemistry?", OPCW, 2019, https://www.opcw.org/sites/default/files/documents/2019/10/The%20Language%20of%20Chemistry-V2.pdf .

straightforward or efficient. Digitized tools that can cross-reference chemical structures with chemical names and other identifiers (such as CAS numbers) and recognize molecular features that meet criteria for inclusion in a schedule would aid in the implementation of regulatory requirements. Machine learning is a useful tool to aid and streamline those tasked with inspecting and verifying regulatory compliance.[92]

For sampling and analysis of scheduled chemicals for CWC verification purposes in a laboratory,[93] the presence of a specific chemical is confirmed by comparison to analytical data of a reference standard. This requires that a standard be available or can be synthesized for comparison when the analysis is performed. AI approaches could also be applied here, providing a means of recognizing characteristic peaks from mass spectral data (or other chemical analysis methods that provide molecular level information) with which to identify molecular structure fragments. From these fragments, the structure (and thus identity) of the unfragmented molecule could be predicted, even in the absence of reference standard data.

Such "standard free" approaches have already been demonstrated for identification of small molecules[94] and metabolites[95] for applications outside the CWC. They are not currently used for CWC verification purposes although the concept has been discussed in some of the laboratories involved with chemical analysis for CWC verification.[96] Confirmation by comparison to analytical data of a reference standard is an established (and trusted) protocol within the OPCW and other international proficiency testing schemes. It is thus conceivable that standard-free approaches that rely on algorithm-generated analytical data will meet with resistance – at least until they are more widely used and accepted.

5.4 BEYOND ROUTINE

Beyond these routine practices, AI-enabled digitization and, more specifically, machine learning-driven approaches could play a role in verification. In this context, the SAB and its temporary working groups have provided many relevant recommendations on the future of verification. Some specifically mention data analytics; other recommendations focus on capabilities that could clearly be enhanced through digitization. Yet others consider the added

[92] S. Costanzi, G.D. Koblentz and R.T. Cupitt, "Leveraging Cheminformatics to Bolster the Control of Chemical Warfare Agents and their Precursors", Strategic Trade Review, vol. 6, no. 9, winter/spring 2020, pp. 69–91, https://strategictraderesearch.org/wp-content/uploads/2020/01/Cheminformatics.pdf.

[93] P. Vanninen (ed.), Recommended Operating Procedures for Analysis in the Verification of Chemical Disarmament: Blue Book, University of Helsinki, 2017, http://www.helsinki.fi/verifin/bluebook/.

[94] S.M. Colby et al., "Deep Learning to Generate *in Silico* Chemical Property Libraries and Candidate Molecules for Small Molecule Identification in Complex Samples", Analytical Chemistry, vol. 92, no. 2, 21 January 2020, pp. 1720–1729, https://doi.org/10.1021/acs.analchem.9b02348.

[95] S.P Couvillion et al., "Who Is Metabolizing What? Discovering Novel Biomolecules in the Microbiome and the Organisms Who Make Them", Frontiers in Cellular and Infection Microbiology, vol. 10, article 388, 31 July 2020, https://doi.org/10.3389/fcimb.2020.00388.

[96] J. Lim et al., "Chemical Structure Elucidation from Mass Spectrometry by Matching Substructures", arXiv preprint arXiv:1811.07886, 17 November 2018, https://arxiv.org/abs/1811.07886. See also OPCW, "Report of the Scientific Advisory Board at its Twenty-Sixth Session", SAB-26/1, 20 October 2017, https://www.opcw.org/sites/default/files/documents/SAB/en/sab-26-01_e_.pdf, paragraphs 9.6–9.7 and 11.1–11.2.

value of advanced data analysis and digital technologies.[97] In this third category, making use of the data generated from remote sensing technologies is one example.

In non-routine investigations and CWC verification activities, the chemical threat agents of concern might not be listed on the CWC schedules. They might also lack a characteristic marker of exposure (a reaction product of exposure or degradation product of the agent). A further challenge is that in any retrospective analysis of a chemical incident, the chemical agents concerned could have been affected by degradation, environmental fate and transport processes,[98] including metabolism by plants, animals or microbes. Here, AI tools for modelling environmental fate and transport could provide valuable information to inform investigative activities. So too might AI-enabled tools to recognize and predict chemical species resulting from metabolic processes initiated after a suitable sentinel species of vegetation is exposed to a specific chemical.[99] The analysis of metabolomic profiles with AI tools could potentially overcome the challenges associated with chemicals such as chlorine gas, which, unlike organophosphorus nerve agents,[100] do not have a recognized characteristic marker of exposure.[101]

In such a case, a supervised (machine) learning approach could process chemical analysis data to find patterns of chemicals and characteristic metabolite markers of exposure in samples collected at the incident site that correlate with exposure to a specific chemical threat agent. In the absence of a training data set containing the full breadth of chemical information required for a truly predictive capability, an unsupervised machine learning approach might work better. An unsupervised machine learning approach could recognize "unusual" phenomena, such as an unusual pattern of metabolic chemical products when compared to the same unexposed vegetation.

Capabilities for recognizing unusual chemical exposure in the environment through a combination of remote sensing and AI tools could draw on technology developed for

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97 OPCW, Verification, Report of the Scientific Advisory Board's Temporary Working Group, SAB/REP/1/15, June 2015, https://www.opcw.org/sites/default/files/documents/SAB/en/Final_Report_of_SAB_TWG_on_Verification_-_as_presented_to_SAB.pdf; "Innovative Technologies for Chemical Security", Chemistry International, vol. 40, no. 4, October 2018, pp. 36–37, https://doi.org/10.1515/ci-2018-0429; and OPCW, Investigative Science and Technology, Report of the Scientific Advisory Board's Temporary Working Group, SAB/REP/1/19, December 2019, https://www.opcw.org/sites/default/files/documents/2020/11/TWG%20Investigative%20Science%20Final%20Report%20-%20January%202020%20%281%29.pdf

98 C.M. Timperley et al., "Advice on Chemical Weapons Sample Stability and Storage Provided by the Scientific Advisory Board of the Organisation for the Prohibition of Chemical Weapons to Increase Investigative Capabilities Worldwide", Talanta, vol. 188, 1 October 2018, pp. 808–832, https://doi.org/10.1016/j.talanta.2018.04.022.

99 M. Bagheri et al. "Examining Plant Uptake and Translocation of Emerging Contaminants Using Machine Learning: Implications to Food Security", Science of The Total Environment, vol. 698, article 133999, 1 January 2020, https://doi.org/10.1016/j.scitotenv.2019.133999. See also D. Toubiana et al., "Combined Network Analysis and Machine Learning Allows the Prediction of Metabolic Pathways from Tomato Metabolomics Data", Communications Biology, vol. 2, article 214, 18 June 2019, https://doi.org/10.1038/s42003-019-0440-4.

100 H. John et al. "Fatal Sarin Poisoning in Syria 2013: Forensic Verification within an International Laboratory Network", Forensic Toxicology, vol. 36, January 2018, pp. 61–71, https://doi.org/10.1007/s11419-017-0376-7.

101 OPCW, "Summary of the Second Meeting of the Scientific Advisory Board's Temporary Working Group on Investigative Science and Technology", SAB-28/WP.2, 21 January 2019, https://www.opcw.org/sites/default/files/documents/2019/01/sab28wp02(e).pdf, paragraphs 13.1–13.7. See also OPCW, "Summary of the Fourth Meeting of the Scientific Advisory Board's Temporary Working Group on Investigative Science and Technology", SAB-29/WP.1, 25 November 2019, https://www.opcw.org/sites/default/files/documents/2019/11/sab-29-wp01(e).pdf, paragraphs 10.5–10.7.

agricultural applications.[102] Already, AI-enabled remote sensing is being deployed to provide farmers with real-time actionable information on plant health.[103] The feasibility of using precision agricultural approaches for recognizing exposure to dangerous chemicals has been explored.[104] Machine learning algorithms to diagnose plant diseases from digital images of plant stress have also been developed.[105] This use of AI to derive meaningful information from visual inputs such as digital images is often referred to as "computer vision".[106] Applications of computer vision extend well beyond plants. For example, a machine learning-based method to identify chemical munitions from digital images can easily be envisioned. This could be realized as a mobile app that helps those handling and disposing of old and abandoned munitions.[107] Considering the large amount of old and abandoned chemical munitions declared to the OPCW, a wealth of imagery that could be used to train algorithms is probably available from States parties and the OPCW's Technical Secretariat.[108] The use of computer vision to recognize and classify sea-dumped munitions has already been demonstrated.[109]

5.5 THE PROSPECT OF DIGITIZED VERIFICATION

The types of system discussed above represent only a fraction of the possibilities that the AI domain might ultimately bring to chemical weapons-related verification. If the CWC regime were to adopt these for verification, States and other stakeholders would need to consider a number of factors beyond just capability, including the relative advantages (and disadvantages) compared with existing, accepted technologies; the availability of suitable and relevant datasets; the costs of such systems; and whether the outputs of these systems are consistently trustworthy.

One consideration is that the adoption of new tools and methods is no easy task for an international agreement like the CWC. Such tools can generate results that inform decisions of considerable consequence for treaty implementation. As such, validation and field testing

[102] OPCW, "Report of the Scientific Advisory Board on Developments in Science and Technology for the Fourth Special Session of the Conference of the States Parties to Review the Operation of the Chemical Weapons Convention", RC-4/DG.1, 30 April 2018, https://www.opcw.org/sites/default/files/documents/CSP/RC-4/en/rc4dg01_e_.pdf, paragraphs 227–229.

[103] K. Liakos et al., "Machine Learning in Agriculture: A Review", Sensors, vol. 18, no. 8, August 2018, article 2674, https://doi.org/10.3390/s18082674.

[104] M.T. Kuska, J. Behmann and A.-K. Mahlein, "Potential of Hyperspectral Imaging to Detect and Identify the Impact of Chemical Warfare Compounds on Plant Tissue", Pure and Applied Chemistry, vol. 90, no. 10, October 2018, pp. 1615–1624, https://doi.org/10.1515/pac-2018-0102.

[105] S.P. Mohanty, D.P. Hughes and M. Salathé, "Using Deep Learning for Image-Based Plant Disease Detection", Frontiers in Plant Science, vol. 7, article 1419, 22 September 2016, https://doi.org/10.3389/fpls.2016.01419.

[106] IBM, "Computer Vision: Use Machine Learning and Neural Networks to Teach Computers to See", https://www.ibm.com/topics/computer-vision.

[107] D. Anelli, "Old Chemical Weapons: Moving the OPCW to an Active Role", Arms Control Today, June 2020, https://www.armscontrol.org/act/2020-06/features/old-chemical-weapons-moving-opcw-active-role.

[108] OPCW, "Draft Report of the OPCW on the Implementation of the Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on Their Destruction in 2019", EC-94/3, C-25/CRP.1, 7 July 2020, https://www.opcw.org/sites/default/files/documents/2020/07/c25crp01%20ec9403(e).pdf , paragraphs 1.15–1.19.

[109] Y. Song et al., "Iterative Refinement for Underwater 3D Reconstruction: Application to Disposed Underwater Munitions in the Baltic Sea", International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XLII-2/W10, 17 April 2019, pp. 181–187, https://doi.org/10.5194/isprs-archives-xlii-2-w10-181-2019; A.S.M. Shihavuddin et al., "Automated Detection of Underwater Military Munitions Using Fusion of 2D and 2.5D Features from Optical Imagery", Marine Technology Society Journal, vol. 48, no. 4, July/August 2014, pp. 61–71, https://doi.org/10.4031/mtsj.48.4.7; and P.-P.J. Beaujean, L.N. Brisson and S. Negahdaripour, "High-Resolution Imaging Sonar and Video Technologies for Detection and Classification of Underwater Munitions", Marine Technology Society Journal, vol. 45, no. 6, November/December 2011, pp. 62–74, https://doi.org/10.4031/mtsj.45.6.6.

of results would most certainly be called for. In turn, this requires appropriate datasets for training, validation and testing – but this may not be achievable in a manner that provides some stakeholders with the level of trust in the method that they require.

Other considerations include security concerns about the vulnerabilities of digitized systems. There is not space here to discuss these considerations in detail, but they would weigh heavily in any debate about adopting AI-driven methods for verification. In an international forum, it is also important to consider that AI tools could be perceived very differently among stakeholders.[110] This may create difficulties in reaching agreement to roll out such technologies. Debates on the trustworthiness, reliability and ethical uses of AI-based methods are not unique to disarmament and non-proliferation – they are now ongoing across the spectrum of AI application areas, for instance in the context of autonomous cars, algorithmic criteria for financial services and the use of AI for intelligence purposes.[111] The outcomes of these debates might help to inform and guide future adoption of analogous technology in the verification domain.

Going forward, discussing use cases and debating how digitization can be seized upon for verification is also valuable in developing a realistic and scientifically and technologically literate common view on the intriguing opportunities of digitized technologies, as well as the areas of concern. A science-based treaty like the CWC must be implemented with a forward-looking vision on science and technology in order to be effective. While technology does not provide solutions on its own, it can help to support and strengthen these efforts. If technological change is viewed from only a perspective of fear, it puts WMD-related regimes like the CWC at a disadvantage.

110 S. Fatima, K.C. Desouza and G.S. Dawson, "How Different Countries View Artificial Intelligence", Brookings Institution, 18 June 2020, https://www.brookings.edu/research/how-different-countries-view-artificial-intelligence/.

111 M. Brundage et al., "Toward Trustworthy AI Development: Mechanisms for Supporting Verifiable Claims", arXiv preprint arXiv:2004.07213, 20 April 2020, https://arxiv.org/abs/2004.07213; and W.D. Heaven, "If AI is Going to Help Us in a Crisis, We Need a New Kind of Ethics", 24 June 2020, MIT Technology Review, https://www.technologyreview.com/2020/06/24/1004432/ai-help-crisis-new-kind-ethics-machine-learning-pandemic/; and Office of the Director of National Intelligence, "Principles of Artificial Intelligence Ethics for the Intelligence Community", https://www.intelligence.gov/principles-of-artificial-intelligence-ethics-for-the-intelligence-community.

6 REFLECTIONS

No single technology will provide a silver-bullet solution to the challenges faced in WMD-related regimes. Moreover, the technologies and approaches discussed here are not readily transferable from one WMD regime to another. However, it is possible to identify some instances in which there is potential for cross-regime transfer and adoption.[112] For example, some of the developments outlined in section 2 of this report on chemical agent detection and section 5 on artificial intelligence (AI) and digitization could be adapted for use in the biological weapons regime. Subsequent papers in this series will discuss the applicability of these technologies in different regimes.

However, to fulfil the potential of novel technologies in WMD treaty monitoring and investigation, stakeholders will need to give due consideration to factors beyond technological requirements. Technological innovation and uptake are related but distinct phenomena. The reality is that the introduction of the kinds of technologies for compliance purposes discussed in this report will be mediated by social, economic and political factors that may have little to do with the efficacy of the specific technology itself, as observed in several of the essays.

The adoption of innovative science and technology for monitoring and investigation of WMD compliance is neither inevitable nor immediate. Indeed, the wider academic literature points to a process whereby organizations adopt new technology.[113] This process often takes time, particularly in public sector organizations, which frequently have less flexibility and "greater reliance on rules and procedures" than their private sector counterparts.[114] It is challenging for these organizations to be nimble, if simply because the States that ultimately fund and govern them not only have differing political positions on specific issues but also have differing appetites for risk. New technologies may be viewed as complex, biased, discriminating, unproven or overly expensive.

This means that, for WMD-related treaty organizations, technological adoption requires "overcoming a 'political ceiling' and putting in place frameworks through which technology could be validated and collectively accepted by States".[115] Table 2 provides an overview of some of the economic and political factors to consider in seeking to make better use of additional technologies for monitoring and investigating compliance.

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[112] For example, in the case of the biological weapons regime, remote monitoring systems could aid assessments of activities at a site over time (see section 2.3); the digitization of an investigation site (section 2.5) could assist any theoretical investigation; whereas the emerge of a Biotechnology 4.0 could theoretically streamline future regulatory reporting under the BWC.

[113] E.g. E.M. Rogers, Diffusion of Innovations, Simon and Schuster, 2010.

[114] F. Damanpour and M. Schneider, "Characteristics of Innovation and Innovation Adoption in Public Organizations: Assessing the Role of Managers", Journal of Public Administration Research and Theory, vol. 19, no. 3, July 2009, pp. 495–522, https://doi.org/10.1093/jopart/mun021.

[115] J. Revill, A. Ghionis and L. Zarkan, "Exploring the Future of WMD Compliance and Enforcement: Workshop Report", WMD Compliance and Enforcement Series Workshop Report, UNIDIR, 2020, https://unidir.org/sites/default/files/2020-04/UNIDIR%20WMD%20CE%20Series%20-%20Workshop%20Report.pdf , p. 11.

TABLE 2 *Wider requirements for the adoption of technology for monitoring and investigating WMD treaty compliance*

Access to Expertise	Realizing the potential of new technologies will require access to technical expertise. In some cases, such expertise may already be available within States and relevant international organizations such as the IAEA Secretariat. In other cases, international organizations may need to acquire additional expertise, including from external organizations.[116] In turn this may require the cultivation of relations with other regimes and organizations and, in some cases, the development of service-level agreements or memoranda of understanding. It will also require building capacity to use novel technologies and to collect, process and analyse data across a much more diverse range of countries.
Access to equipment	To exploit new technologies, international organizations and States may require access to specific equipment. Although some tools may be available commercially off-the-shelf (COTS), other equipment, such as UAV-mounted CWA detectors, may need to be customized to meet the specific needs of the user.[117] In some cases, international organizations or States may be the only buyers in the market, which can result in increased costs.[118] Obtaining access to advanced equipment may also be problematic as some technologies are sensitive and subject to export control policies that may impose restrictions on the locations of use.
Validation of technology	Without a convincing demonstration of the accuracy or reliability of a new technology for WMD-related regimes, States will not accept their use. The confidentiality, integrity and security of the data collected via these technologies is also critical, not only for the international organization collecting the data, but also for States from which data is being collected in order for them to be confident that it is properly protected from unauthorized access (see also below on validation of methods) and preserved in storage over time. Validation of new technologies in advance of their use will therefore be essential in each of the WMD regimes.

[116] For example, examination of open-source "social media" data will require expertise in digital forensics, which may be located within the law enforcement community.

[117] M. Stein and B. Richter, "A Sustainable Approach for Developing Treaty Enforcement Instrumentation", In R. Avenhaus et al. (eds), Verifying Treaty Compliance, Springer, 2006, pp. 559–571, https://doi.org/10.1007/3-540-33854-3_27.

[118] As Stein and Richter note: "Safeguards-specific instruments have a low potential of attracting customers outside their niche market. This puts the IAEA into a monopsonistic position, as the only buyer of Safeguards systems". Ibid, p. 560.

Validation of methods	The methods for using technologies will also need to be validated and agreed by States in advance. Agreement on methods and guidelines are important in armour-plating new approaches against procedural or methodological criticism.[119] However, care will need to be taken to ensure that methods are not overly prescriptive and can be adapted to a wide range of possible scenarios. International organizations need to ensure that staff are suitably trained in the use of relevant technologies in accordance with agreed methods.
Information management	In 2019, the Director General of the IAEA stated that the agency handled 140 million items of open-source data every year.[120] As new sources of data of relevance to compliance continue to emerge, information management will become increasingly important. In cases where machine learning technologies are being considered it will also be important to develop adequate and suitable data sets with which to inform the process of machine learning.
Expectation management	The technologies discussed above typically provide only one possible indicator of non-compliance. Assessing compliance will require multiple indicators. As such, the expectations of States need to be managed, including through forthright evaluation of the strengths and limitations of these technologies.
Cross-regime collaboration	Cross-regime collaboration will be required to fulfil the potential of some of the technologies discussed above. For example, making the most of open-source trade data may require collaboration between the BWC and the World Customs Organization.
Political backing	The efficacy of science and technology in support of monitoring and investigation of WMD compliance will ultimately depend on the extent of the political support it has among the member States of each regime. Some technologies, no matter how technically advantageous, are likely to remain unacceptable for use in compliance monitoring or assessment.[121] One variable in this equation is the broader strategic climate and level of tension. At this juncture, tensions and divisions between States in some WMD treaties, such as the CWC, could complicate the adoption of new tools for investigating non-compliance without careful preparation and collective political backing.

[119] J.N. Cooley, "International Atomic Energy Agency Safeguards under the Treaty on the Non-Proliferation of Nuclear Weapons: Challenges in Implementation", In R. Avenhaus et al. (eds), Verifying Treaty Compliance, Springer, 2006, pp. 61–76, https://doi.org/10.1007/3-540-33854-3_4. See also M. Daoudi and R. Trapp, "Verification under the Chemical Weapons Convention", Ibid, pp. 77–106, https://doi.org/10.1007/3-540-33854-3_5; and K. Mayer, M. Wallenius and I. Ray, "Tracing the Origin of Diverted or Stolen Nuclear Material through Nuclear Forensic Investigations", Ibid, pp. 389–408, https://doi.org/10.1007/3-540-33854-3_18.

[120] Y. Amano, "Challenges in Nuclear Verification", IAEA, 5 April 2019, https://www.iaea.org/newscenter/statements/challenges-in-nuclear-verification.

[121] For example, despite the technological potential for machine learning-based systems, states are unlikely to accept the "results" from black box machine learning systems, the methodologies of which are neither transparent not readily understandable. See K. Brockmann, S. Bauer and V. Boulanin, Bio Plus X: Arms Control and the Convergence of Biology and Emerging Technologies, Stockholm International Peace Research Institute, March 2019, https://www.sipri.org/publications/2019/other-publications/bio-plus-x-arms-control-and-convergence-biology-and-emerging-technologies.

These wider requirements are a reminder of the need for a healthy dose of realism when considering the adoption of new technologies in support of compliance with and enforcement of WMD-related treaties. Overall, these are factors that require prudence rather than necessarily constituting obstacles. That they may crop up should not discourage efforts to examine the opportunities presented by science and technology for improving compliance and enforcement. As regimes concerned with ensuring that science is not turned to hostile use, the WMD treaties depend critically on adapting to scientific and technological advances – and that entails capitalizing on these trends when it makes sense to do so. Governments, as well as other responsible stakeholders in science, industry and civil society, all have roles to play in supporting this endeavour.

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