Mapping the Influence of Disruptive Technologies on Future Arms Control Agreements.

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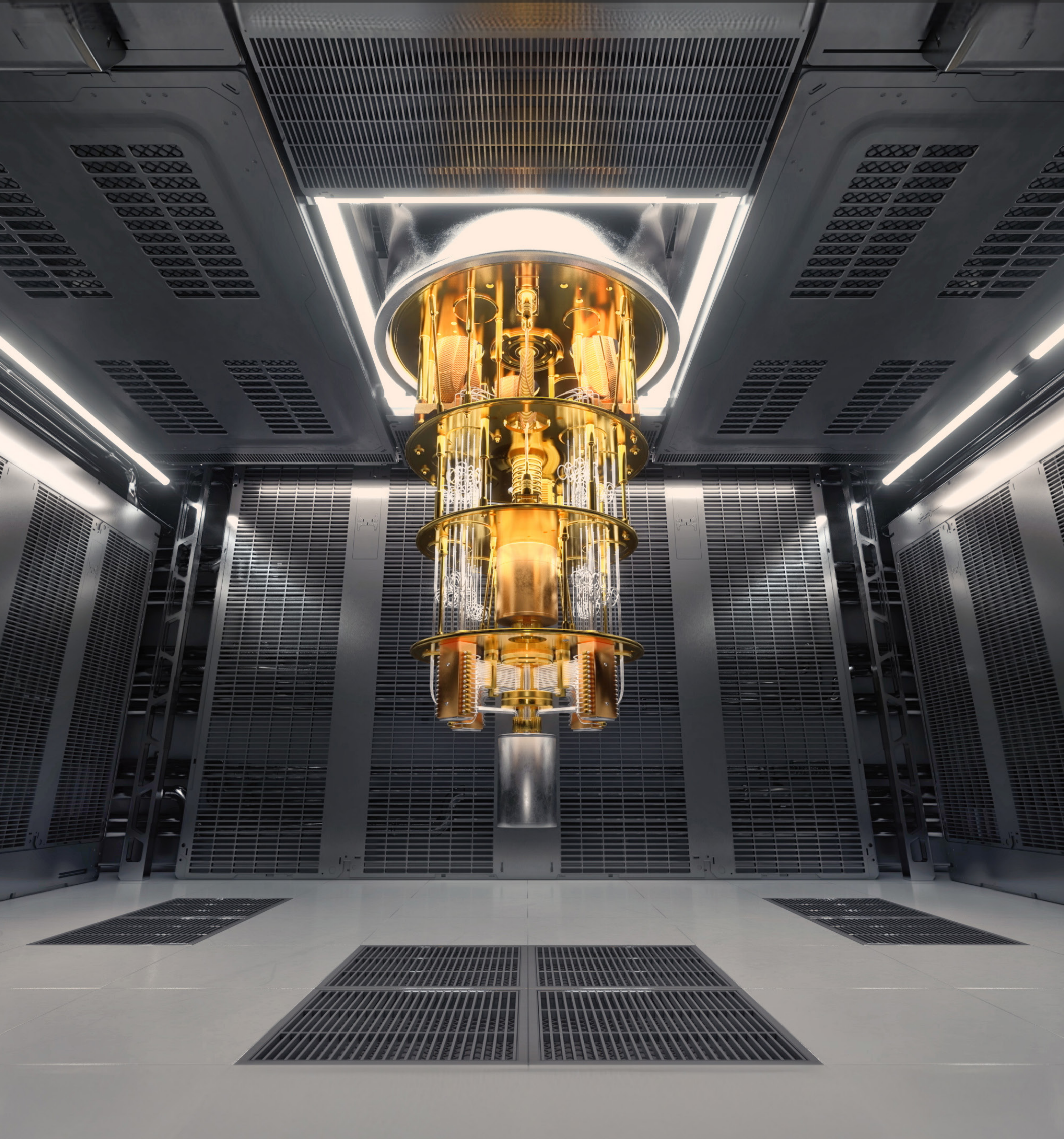

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Défense nationale National Defence

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His research and policy interests occur at the nexus between space, nuclear systems, security, and policy, where he deploys mixed-methods and futures analysis to examine the interplays between technological development and the complex policy contexts within which it occurs.

BASIC

BASIC is a London-based think tank that promotes meaningful dialogue amongst governments and experts in order to build international trust, reduce nuclear risks, and advance disarmament. We have a global reputation for convening distinctive and empathic dialogues that help states overcome complex strategic and political differences. Our established networks and expertise, developed since 1987, enable us to get the right people in the room and facilitate effective, meaningful exchange between siloed and often hostile political communities.

Contents

Executive Summary

Future arms control measures between the major powers are likely to be multilateral and asymmetric, and cut across weapon systems and strategic domains. Yet, the growing complexity of the international system – in terms of the sheer number of actors, security interests and perceptions, weapon systems, and the feedback loops between them – makes it difficult for policy makers to identify workable multilateral agreements. Couple this complexity with emerging technologies (or novel use cases for existing ones) and the picture muddies further.

BASIC mapped 22 technological trends that may influence one of three areas of arms control in the future: a) the form and function of the nuclear weapons themselves; b) the monitoring and verification of arms control agreements; and, c) the conditions in which any new agreement must be negotiated. Each technological trend was assessed for the mechanism by which it influences arms control in future should it develop to its potential, the level of influence it would exert on arms control at its potential peak[1], the outlook for that trend given the current state of play and future challenges; and the indicators or issues to monitor that might indicate rapid progression of that trend. This research avoids timelines where possible as they are subject to change, instead focusing on the trajectory to maximum impact of a trend, and identifying the key indicators along the way. We also identified enabling / inhibiting interactions between trends, and make that available in the Annex.

This analysis was validated through interviews with subject matter experts from outside the nuclear policy space, and the result was clear: emerging technologies will drastically change the world in which nuclear weapons exist, but not the weapons themselves. The key takeaways from this research were:

1. The form and function of nuclear weapons are unlikely to change substantively, even over the long-term, but the conditions in which arms control agreements must be negotiated will be drastically different than they are today, driven by major societal changes as AI's become more integral to the functioning of states – the geopolitical reality of 2034 or 2044 is impossible to predict, and therefore work undertaken today to re-establish arms control has real future value.

2. The advent of reliable autonomous decision making AI's will drive much of the rapid changes to the security landscape, enabling autonomous cyber-agents for high-volume attack and defence, and persistent autonomous underwater operations, as well as providing analysis for governments across almost all of their activities.

3. Whilst advancements in materials, computation, and manufacturing are going to occur and have substantive impact on the world around us, they will occur as the accretion of incremental improvements, and therefore can be monitored and observed, and therefore planned for.

The map on the following pages (6-7) shows how most of the influence of new or emerging technologies filters down to the wider global context. The full interactive version of the map is available here, where users can click on individual connections and nodes to receive more information on the mechanism by which a trend influences arms control in future, as well as access some further reading links.

1 Using modified Likert language of "somewhat influential", "influential", "very influential", and "step-change".

Technological Trends of Interest

BOX 1

Additive Manufacturing

Autonomous Computer Network Operations

Autonomous Decision Making

Autonomous Nuclear Reactors

Autonomous Underwater Operations

Biocompatible Materials

Brain-Computer Interfaces

Decision Support AI for Civil Purposes

Decision Support AI for Military Purposes

Digital Twins

Generative AI – Materials

Generative AI - Media

High Entropy Alloys

High Temperature Superconductors

Lethal Autonomous Weapons

MAX-Phase Materials

Metamaterials

Quantum Computing

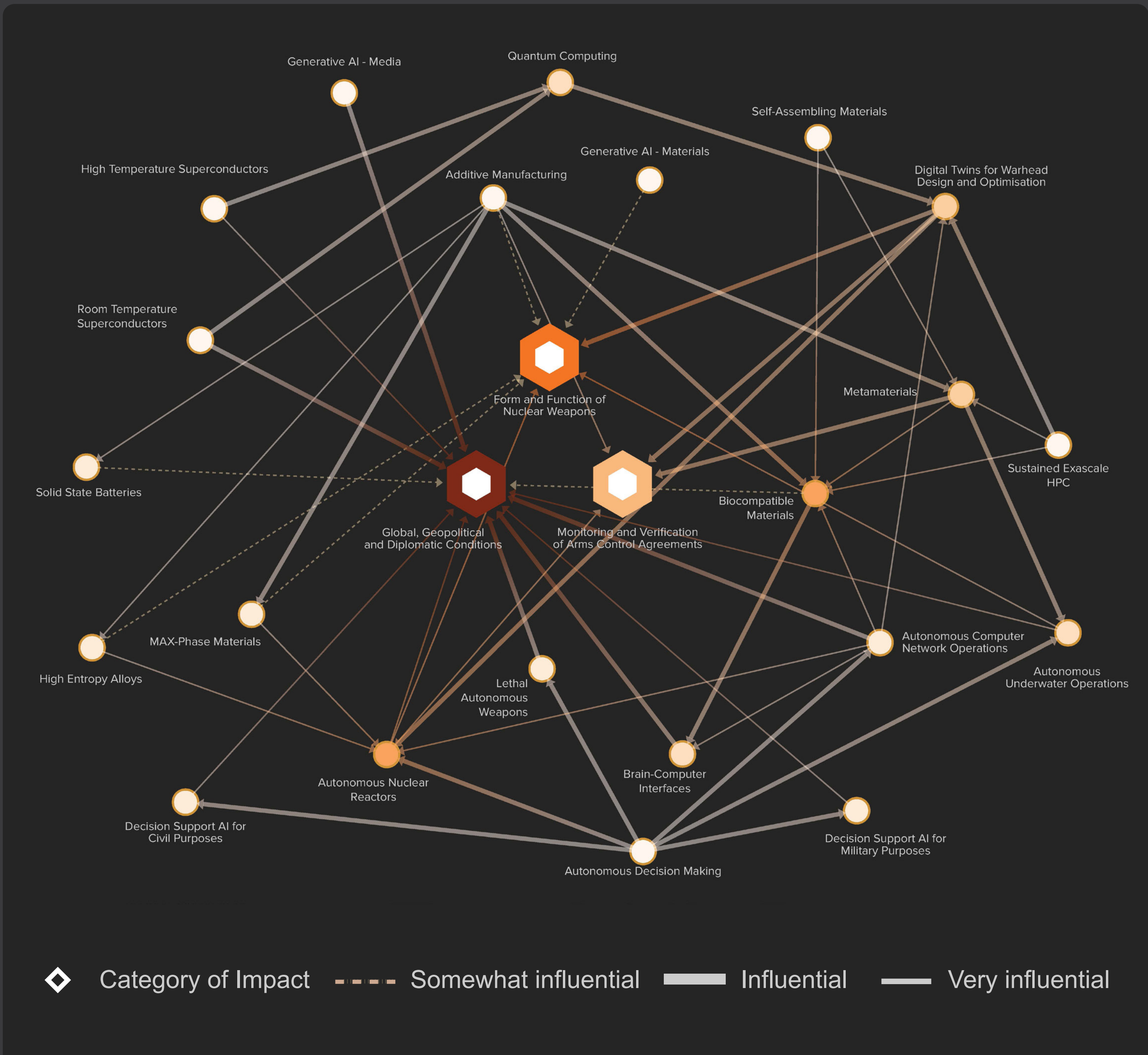
Room Temperature Superconductors

Self-Assembling Materials

Solid State Batteries

Sustained Exascale High Performance Computing

FIGURE 1



A Kumu landscape map of emerging technological trends and their influence on a) the form and function of the nuclear weapons themselves; b) the monitoring and verification of arms control agreements; and, c) the conditions in which any new agreement must be negotiated. A node's colour indicates its "indegree", a measure of the number of incoming connections to it – those nodes are most influenced by others.

Introduction

The ability to anticipate and adapt to future scenarios is paramount for all states. In this report, we assess how emerging or novel technologies drive changes to the form or function of nuclear weapons, and therefore arms control efforts. Technology actively shapes the capabilities of nations, influencing alliances, partnerships, and adversary dynamics, but this report also recognizes that non-technological factors play a significant role, creating environments where specific technologies or applications can flourish, and vice versa. These challenges are intricately interwoven, forming complex feedback loops that will both influence and reinforce each other over the coming decades.

This report focuses specifically on technological trends in three key areas – limited memory AI and autonomy; materials and manufacturing; and computation. It assesses each for their future influence over the shape and character of nuclear weapons and their delivery systems as well as the monitoring and verification of arms control agreements, and the conditions in which they must be negotiated. We avoid the use of specific timeframes given how tightly enmeshed and interdependent many of these trends are, and instead provide key indicators, or technical milestones, that should be monitored. Understanding where we are on the trajectory is more useful than an estimate of when it will become material. To that end, we performed a desk-based technological landscape survey before a round of expert interviews to validate and refine the results. The full database is available in the Annex.

We argue that alongside technologies that may alter the form or function of a nuclear weapon, equal consideration should be given to technologies shaping the geopolitical context in which future arms control agreements are negotiated. By acknowledging this broader perspective, the report aims to provide a more comprehensive and insightful framework for strategic decision-making. This analysis is then used to provide tailored interventions for the Department of National Defence and the Canadian Armed Forces (DND/CAF) on arms control and risk reduction in the near, medium, and long terms, as well as for the wider community.

For each trend identified in the landscape survey, we asked:

1. Does this technology have the potential to materially impact the form or function of a nuclear weapon or delivery system? If yes, what is the specific mechanism by which it achieves that impact?

2. Does this technology have the potential to materially impact monitoring and verification in arms control agreements? If yes, what is the specific mechanism by which it achieves that impact?

3. Does this technology have the potential to materially impact the conditions in which arms control agreements are to be negotiated? If yes, what is the specific mechanism by which it achieves that impact?

4. Does this technology enable or inhibit the trajectory of technologies assessed elsewhere in this report? If yes, how strong is that influence (step-change, very influential, influential, or somewhat influential)[2]?

5. Does this technology represent a “Step-Change” for nuclear weapons design, the wider global context, or arms control agreements?

Taking the results of this assessment, we mapped the technologies and their webs of influence using Kumu. These maps are interactive and descriptive, and are available at this link, and we encourage readers to engage with them, but static versions are also provided as visual aids in this report. The text-based analysis is available in the Annex to this report.

2 See Box 1 on pages 6 - 7

Outcomes from the Expert Interviews

One of the key outcomes from our expert interviews was that there are precious few step-changes in the near-medium term technological pipeline that would directly influence the form or function of a nuclear weapon. While hypersonic glide vehicles, or nuclear-powered ramjets may provide novel capabilities, they are unlikely to make ICBMs or SLBMs obsolete, and will likely make up an extremely niche subset of strategic weapons. The vast majority of the technological advancements are incremental – but not necessarily linear. For arms controllers present and future (and policymakers in general), this is good news, as with proper monitoring of technological trends, there should be correspondingly few strategic surprises.

Our experts agreed that the incremental nature of the trends that influence nuclear weapons mean that focus should be shifted to mitigating the influence of emerging technologies on global diplomatic, social, and geopolitical conditions. As a result, the majority of the recommendations below are aimed at reducing the relevance of nuclear weapons, or creating the conditions for a return to arms control. Each recommendation also notes the actors responsible for implementing to allow CAF/DND to prioritise any recommendations that are actionable unilaterally or with limited friction.

Step-change vs Incremental Advances

BOX 2

Step-changes, also known as disruptive innovations, introduce entirely new technologies that create entirely new capabilities or significantly disrupt existing ones. These innovations often involve paradigm shifts, challenging the underlying principles of existing technologies and offering a completely new way of achieving a function. Step-changes can bring about rapid performance improvements in areas like speed, efficiency, or capabilities. However, developing and deploying these technologies often require substantial upfront investment in research, development, and infrastructure. Examples of step-changes include the invention of the transistor, the emergence of the internet, and the rise of social media platforms.

Incremental advances, on the other hand, represent gradual improvements to existing technologies. They build upon existing knowledge and refine established technologies, increasing efficiency, reliability, or user experience. They lead to a steady but measurable improvement in performance over time, such as increased processing power and memory capacity in computers, improved battery life for smartphones and laptops, and the development of new software features and functionalities, but are subject to engineering and physical limits such as power density for batteries.

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Summary of Results

Limited Memory AI and Autonomy

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It's reasonable to assume that within the next decade, we can expect AI to become firmly embedded in our daily lives with personalised experiences in education, healthcare, and entertainment, driven by intelligent systems that anticipate our needs and preferences may become commonplace.

The reality, however, may be starkly different, with digital divides widening domestically, regionally, and globally – not to mention those same personalised services being leveraged against individuals, intentionally or otherwise. These global trends are likely to play an outsized role in generating the conditions under which new arms control agreements must be negotiated.

AI's capacity for sound, reliable reasoning and decision making within specific domains will drive the strategic-level changes. Enabling autonomous cyber-agents for attack and defence at a rate substantially higher than present, and persistent autonomous underwater operations that could hold SSBNs at risk in choke points, as well as providing analysis for governments across almost all of their activities including diplomacy and foreign policy.

Policy Recommendations

Recommendation №1: Continue to work with allies, partners, and adversaries to re-establish the conditions for arms control

Working with allies and partners to understand where concessions can be made in any future negotiations and conducting research to identify the central feedback loops which have stymied progress on arms control, should form core tenets of any effort to re-establish the conditions for it.

Recommendation №2: Develop strong verification processes for mis-/disinformation

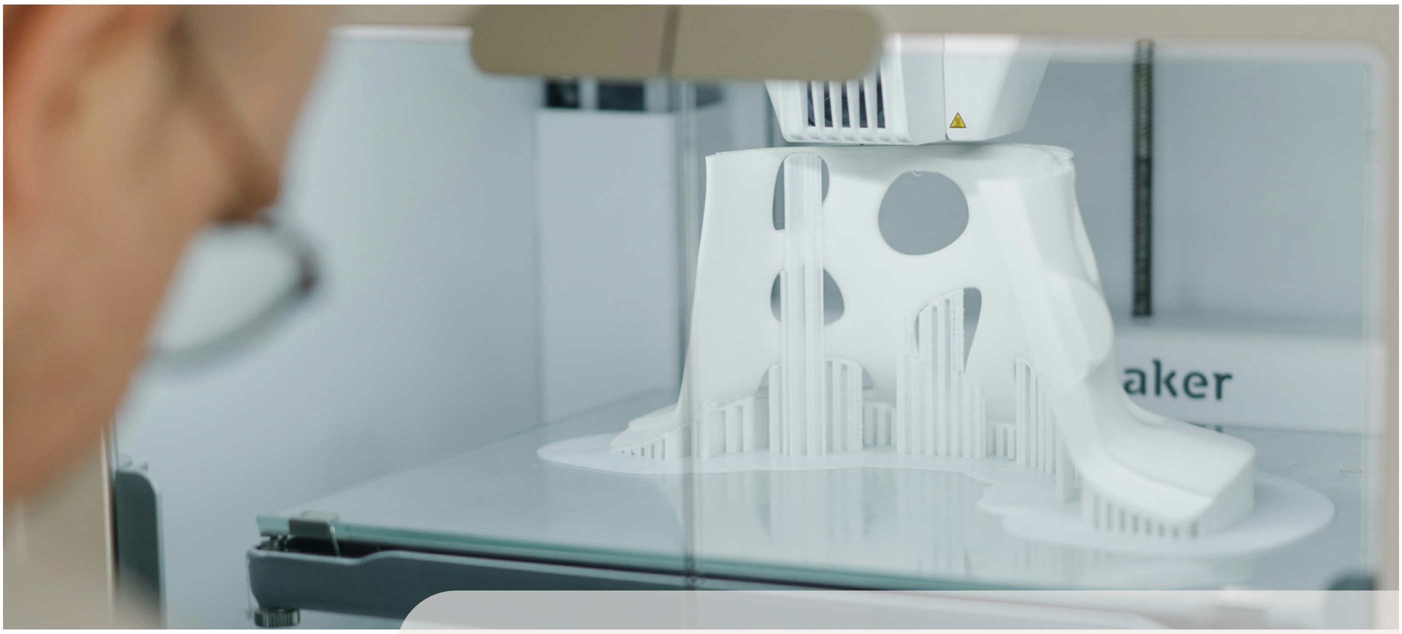
Governments across the world should spend the coming years developing rapid and robust verification tools and protocols for AI-generated content to counter the spread of mis-/disinformation, especially where it concerns nuclear weapons.

Recommendation №3: Stand up public facing technology monitoring groups

Establish advisory groups for technologies of interest, with secretariat function outsourced to relevant research institutions to semi-passively monitor the technological landscape for indicators of progress for influential technologies.

Materials and Manufacturing

Photo by Tom Claes - Unsplash.com



Materials science and engineering is everywhere, embedded in every physical, artificial system.

Selecting materials can be straightforward or wickedly complex, depending on the function of the component you are selecting for. If the environment that it must operate within is corrosive, radioactive, sensitive, very hot, very cold, mechanically abrasive, under extreme loading, or some combination of these, then materials selection has an enormous influence on the performance of that component. Given that many nuclear weapons systems, current and future, operate in some combination of the environments above, that makes materials science a key facet of the relevant technological ecosystem. The mission-critical nature of nuclear weapons means tolerance for failure is extremely low as an unreliable weapon has limited deterrence value. The 2023 room-temperature superconductor false alarm demonstrated that a genuine step-change in materials science would have a profound influence in every domain, but also that they are rare and unlikely to be the panacea we expect – the material described in 2023 was mostly lead, which is a very poor engineering material, and toxic. However, atomically designed bulk materials are in laboratories, and making their way into specialist applications where the cost is warranted when weighed against the performance gain.

Intrinsically linked with materials discovery, development, and application is the physical manufacture of either bulk materials, components, or finished products. The manufacturing landscape is undergoing a major shift, as evolving consumer demands, and new business models change the economics of manufacturing. This is driven by advances in automation, robotics, additive manufacturing, personalisation, and biomanufacture that may – in theory – lead to increased efficiency, customization, and sustainability. The development of digital twins for factories, machines, and perhaps even people, may open new routes to proliferation in the very long term, as aspiring nuclear weapons states complete testing and optimisation in a virtual environment. And while a future characterised by digital twins, fully distributed manufacture, and automated factories is, at best, a very long-term scenario, a manufacturing sector built on those principles could drastically change conflicts, and traditionally stable supply chains.

Computation

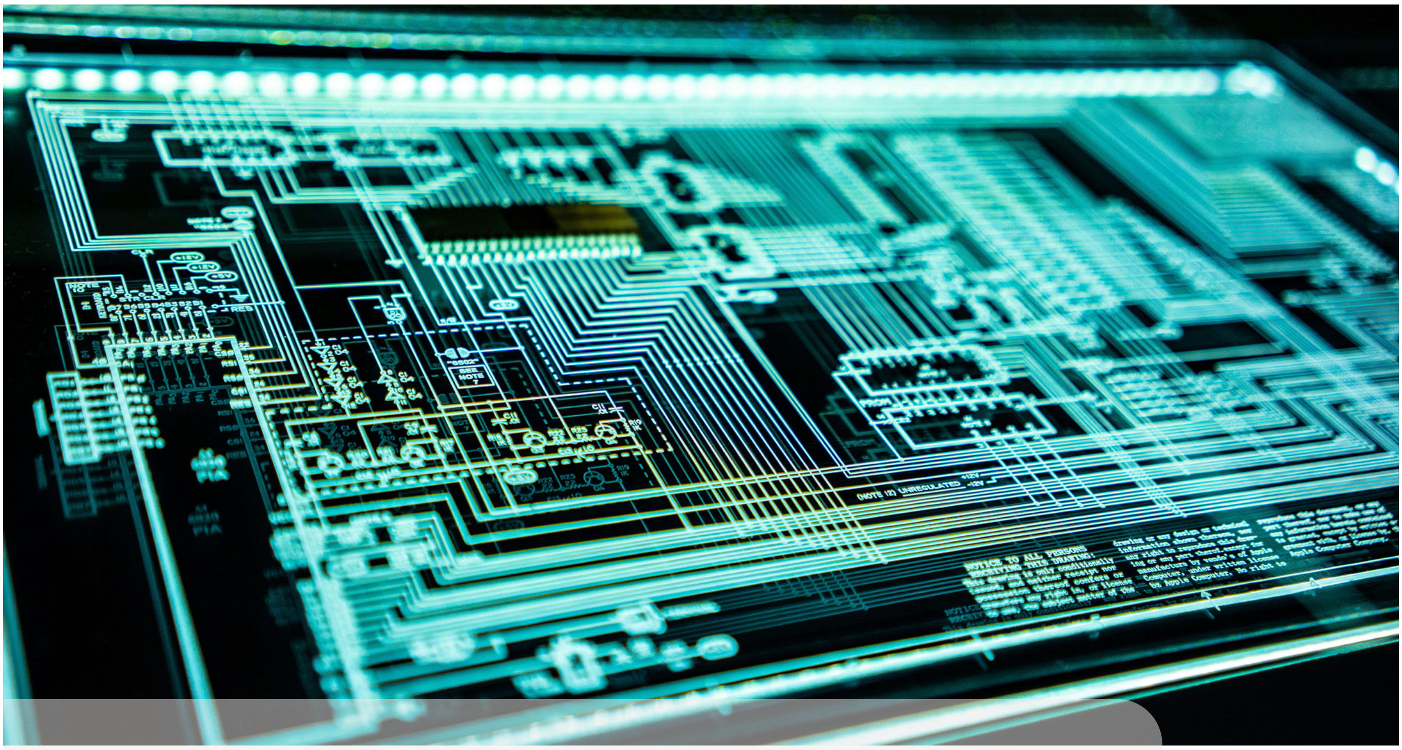


Photo by Adi Goldstein on Unsplash

Moore's Law, the observation that the number of transistors on an integrated circuit doubles every two years with minimal rise in cost, has dominated computational projections for decades, and while the future will certainly be characterised by more powerful processors, the way in which computation is done is also liable to change.

Brain-computer interfaces, allowing direct communication between minds and machines, may reshape how we interact with technology and potentially enhance human cognitive abilities. Bio-inspired computing could lead to more energy-efficient and adaptable computational processes. The physical place where the computation is done may change, away from centralised remote servers and towards the place where the data originates.

But Moore's Law is still important, and the future of high performance computing (HPC) is sustained exascale computing. Defined by its ability to perform in excess of one exaflop, or 10^18 floating-point operations per second, sustained exascale computing would transform scientific and engineering research. Several systems have already met that criterion, including Aurora at Argonne National Laboratory (1.8 exaflops) and Frontier at Oak Ridge National Laboratory (1.1 exaflops). Both achieved exascale performance in 2022, but while they showcase the potential, widespread accessibility across research institutions and diverse applications remains a challenge. Building and maintaining such systems is resource-intensive, requiring significant funding, infrastructure, power, and expertise that is only available in a select few of places on Earth. Therefore, it's less about "when" and more about "how", given that it is already a reality for some.

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Recommendations

Photo by Mathias Reding on Unsplash

Recommendation №1: Continue to work with allies, partners, and adversaries to re-establish the conditions for arms control

In the future described in Recommendation №2, (see next page) transparency and clarity will be ever more important. Working with allies and partners to understand where concessions can be made in any future negotiations and conducting research to identify the central feedback loops which have stymied progress on arms control, should form core tenets of any effort to re-establish the conditions for it.

Specifically, and in the medium term, Canada could work with the P3, individually or as a whole, to steadily reduce the ambiguity in their declaratory policies. While removing some option value for strategists, more clarity might a) enhance a state's nuclear deterrent by ensuring that an adversary is aware of the precise conditions for nuclear retaliation[3], and b) set the stage for more transparent conversations with adversaries about threat perceptions. Canada should also continue its support for regularising the bilateral discussions on strategic stability between the US and China in order to provide a space for clarifying intent, and reiterating a desire for peaceable, responsible competition. Simultaneously, it should continue in its pursuit of regular contact between Ottawa and Beijing, especially during times that ministers from both states have called "challenging".

In short, re-establishing arms control is a long-term endeavour requiring sustained commitment, patience, and flexibility. And while the onus remains on the nuclear weapons states, Canada has an important role to play as a close ally of the P3 in facilitating a return to the conditions necessary for arms control. The challenges are significant, but they are not insurmountable yet.

3 Summary of APPG Meeting: Does Britain's Deterrent Policy Need Updating?

Photo by Chaosamran Studio - stock.adobe.com.

Recommendation №2: Stand up public-facing technology monitoring groups

The majority of our experts interviewed agreed that one of the key problems with emerging technology policy and the hype cycle is not that the systems mature overnight, but that policymakers and wider publics are not embedded within the communities that develop them, and likely will never be fully immersed in them. The information is out there but it needs a conduit from the source to the policymakers.

To ensure that DND / CAF has a reliable institutional sense of where technologies of interest are in their development and deployment trajectory, it should embark on a monitoring programme in the form of expert advisory groups. These groups would be similar in scope to others stood up by the Government of Canada, such as the Technical Advisory Committee on Science and Knowledge, and the Advisory Council on Artificial Intelligence. These groups would provide detailed, specific updates on technologies of interest and the implications for Canada's security, and the security of its allies. Establishing an epistemic community for each technology of interest, composed of academics, industry engineers and scientists, and research leads at relevant national laboratories. These groups should meet in a staggered fashion, once or twice a year, producing a steady stream of updates on the cutting edge of capabilities available to Canada, its allies, and adversaries. Each group might produce a briefing report – available to the public – either annually or biannually, and the necessary secretariat function could be performed by relevant university departments or NGOs. The topics we suggest map to the Deep Dives in Annex A, and are as follows:

Autonomy

Decision making AI's that are able to complete complex tasks, with minimal or no input from a human operator, and make sound choices based on their learning history and data on their environment, will fundamentally change a number of nuclear-relevant spaces. Autonomous underwater vehicles (AUVs) in oil and gas exploration and maintenance are a solid indicator of the state of the art in undersea autonomy, with an ever increasing performance envelope. Militarised versions could disrupt communications infrastructure, or patrol choke points en masse, holding SSBNs of allies and adversaries at risk as part of wider strategic anti-submarine warfare operations. Autonomous AI agents can conduct cyberattacks at a pace and volume that human beings are not capable of, and free of human bias, can solve problems in ways we cannot anticipate, which may open up cybersecurity risks across the nuclear enterprise.

Generative AI and the information environment

Ensuring information integrity and trust in the age of large language models and text-to-image/video/audio will be critical to maintaining the international diplomatic conditions necessary for the negotiation of future nuclear arms control agreements. AI that can leverage public opinion over social media may also play a role in democratic processes – and it is important to note that nuclear and global security policy is, by and large, made by governments that are elected through democratic means. Therefore developing robust countermeasures and verification tools, as well as market incentives, to safeguard the information environment must be a priority for Canada and its allies.

Metamaterials

Metamaterials are substances with precise, subwavelength structures to manipulate electromagnetic or other waves to alter the observed properties of that material. For example, an "invisibility cloak" which bends electromagnetic waves (such as optical, or infrared light) around it, rendering the object invisible in that wavelength. There are a multitude of metamaterials relevant to nuclear weapons and the future of arms control. Of particular interest, and in the nearer term, is the development of advanced metamaterials for acoustic stealth or sonar that would permit more effective detection of adversary (or allied) ballistic missile submarines (SSBNs), thereby holding them at risk. The same family of metamaterials may also improve the data transfer rate and range of underwater acoustic communications, which is severely limited by complex bathymetry, permitting remote operation of underwater drones for detecting transiting SSBNs.

Superconductivity and computation

While high temperature superconductors may permit greater efficiency gains in quantum circuits, the computer itself still needs to be cooled to a fraction of a degree above absolute zero. As such, the role for high-temperature superconductors may in fact be in integrating quantum and classical computers that can seamlessly switch between quantum and classical modalities depending on the problem. Optimisation problems are one of the key domains in which quantum computation will be important, and may lend itself well to simulating nuclear weapons, aiding in design and development of such. The remit of this advisory group should also cover the state of the art in classical computing and conventional modelling capabilities.

Photo by Ser - stock.adobe.com.

Recommendation №3: Develop strong verification processes for mis-/disinformation

Governments across the world should spend the coming years developing rapid and robust countermeasures, verification tools, and protocols for AI-generated content to limit the spread of mis-/disinformation, especially where it concerns nuclear weapons.

As one of our experts put it, society is “at the bottom of the curve” when it comes to generative AI, and what comes next may be a revolution in the way in which we receive, consume, and engage with narratives in the information space. This technology opens up the possibility of an abundance of content, personalised experiences, and even automated information production. High volumes of news articles and social media posts that perfectly align with a person’s worldview, yet contain subtle manipulations or even outright falsehoods designed to keep them engaged. Deepfakes and hyper-realistic AI-generated videos, could further blur the lines between truth and fiction, eroding trust in traditional sources and making it increasingly difficult to discern genuine information. This erosion of trust could have far-reaching consequences, impacting everything from individual decision-making to the stability of democratic institutions.

In a world characterised by an abundance of information, much of it personalised and tailored to elicit maximum engagement, where AI agents generate news articles, and even educational materials, it is possible for a sophisticated misinformation campaign to activate large sections of society against arms control, or other diplomatic measures, during a time of deep crisis. States will need a clear sense of how to counter this issue – not just with fact-checking and verification (which rarely convinces those it most needs to), but perhaps through change to the business models or financial incentives that exist in our information space. Incentives could be tuned away from the most engaging emotions towards a more neutral selection of emotions.

DND / CAF should prepare for this future, if it is not already, by engaging with social media companies, developing and commissioning a more substantial evidence base of how content generation activates human emotions, how that contributes to social friction, and working with allies and partners across the globe to share best practice and protocols. Given that this is the world that any future arms control agreement must be negotiated in, and will have material impacts on the policy priorities of the government of the day, protection of this space is critical to advancing arms control.

Conclusion

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The future of nuclear arms control faces a complex and rapidly evolving environment. While the fundamental nature of nuclear weapons may not change dramatically, the geopolitical landscape in which they exist will be significantly reshaped by emerging technologies, particularly the rise of autonomous decision-making AI.

This report mapped and then presented a framework for understanding how these technologies will influence three key areas: the form and function of nuclear weapons themselves, the monitoring and verification of arms control agreements, and the broader security context. While negotiating multilateral and asymmetric arms control agreements will be challenging in this increasingly intricate system, proactive efforts are crucial. By mapping technological trends and their potential impact, policymakers can begin to navigate these complexities and build a foundation for future arms control initiatives, even if the exact geopolitical landscape remains uncertain.

The key takeaway is clear: emerging technologies will not fundamentally alter nuclear weapons, but they will radically transform the world in which they exist. The work undertaken today to re-establish and adapt arms control frameworks will have lasting value in this ever-shifting landscape.

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Technological trends that directly influence nuclear weapon design

Digital Twins for Warhead Design and Optimisation[4]: Very influential

Influence mechanism
Digital twins could be used for front-end development and testing of new or existing weapons systems to rapidly reduce breakout times or develop novel delivery systems with a very small footprint.

Rationale
Rated "very influential" as rapid testing of systems without the consequences of failure or upfront costs (and potentially in secret) could drastically improve, or provide new delivery systems for, existing nuclear weapons.

Outlook and indicators
Barriers to this technology being deployed are significant, requiring enormous computational resources, and technical subject matter expertise.

Indicator(s):
1. Digital twins commonplace in nuclear reactor operations

Autonomous Nuclear Reactors[5]: Influential

Influence mechanism
Compact, autonomous reactors are a key component of nuclear-powered loitering munitions either aerial or submerged.

Rationale
Rated "influential" as is relevant for a small subset of weapons and delivery systems.

Outlook and indicators
Multiple systems are already in the testing phase (Burevestnik, Poseidon), these systems may continue to propagate through nuclear arsenals.

Indicator(s):
1. Burevestnik testing outcomes improve
2. Burevestnik deployed

Autonomous Underwater Operations[6]: Influential

Influence mechanism
Persistent hunting, tailing, and even aggression towards SSBNs by swarms of UUVs at natural choke points could lead to an evolution of SSBN practices and possibly design.

Rationale
Rated "influential" as diesel-electric UUVs cannot match the performance of SSBNs.

Outlook and indicators
Multiple systems are already in the testing phase (Boeing Orca, MSub Manta), these systems may continue to propagate, especially in coastal navies.

Indicator(s):
1. AUVs for oil and gas, conducting fully autonomous inspection, maintenance, and reporting activities.
2. Large orders (>10) of UUV placed with manufacturers.

4 Digital Twins Facilitate Program Success for Sentinel
5 One nuclear-armed Poseidon torpedo could decimate a coastal city. Russia wants 30 of them
6 Is the SSBN Deterrent Vulnerable to Autonomous Drones?

Additive Manufacturing[7]: Somewhat influential

Influence mechanism
Niche use-cases in complex geometry manufacturing, such as coolant channels for re-entry vehicles, or rocket engine.

Rationale
Rated "somewhat influential" as the use cases in the design of nuclear weapons or their delivery systems are not unique and can be performed by other manufacturing processes in the main.

Outlook and indicators
Already widely used in aerospace and beginning to be deployed in nuclear power contexts, matter of if, not when, it is integrated into nuclear weapons supply chains.

Indicators:
1. AM certified for the manufacture of critical nuclear reactor components, such as cladding and fuel pin assemblies.
2. Cases of export control breaches utilising AM occur and grow.

Generative AI - Materials[8]: Somewhat influential

Influence mechanism
AI-enabled material design and discovery has already occurred, and it may in future discover a material useful in the manufacture or function of nuclear weapons.

Rationale
Rated "somewhat influential" as material discovery performed by AI may turn up many thousands of novel crystal structures, but the cost of investigating which are effective, what their properties are, how they can be manufactured etc. is likely to drastically mitigate any potential uses of AI-designed materials in nuclear weapons.

Outlook and indicators
Materials discovery is one thing, but characterisation and certification for use in the nuclear enterprise is another and would require substantial integration of multiple AI-enabled systems and laboratory testing.

Indicator(s):
1. Material first discovered by AI certified for use in nuclear reactors.

High Entropy Alloys[9]: Somewhat influential

Influence mechanism
High performance in austere environments mean that if reliably manufactured in bulk, HEA's could form structural components of hypersonic glide vehicles, or other critical components that must operate in aggressive environments.

Rationale
Rated "somewhat influential" as they enable a small subset of nuclear weapons to be more effective, but share characteristics with other classes of materials.

Outlook and indicators
Currently available in small quantities in specific laboratories, but no bulk manufacture of HEAs with uniform distribution of elements (and thus uniform, predictable material properties).

Indicator(s):
1. Bulk manufacture of HEA
2. HEA used in commercial context.

7 Fact Sheet: Additive Manufacturing
8 Artificial Intelligence for Accelerating Nuclear Applications, Science and Technology
9 What Are High Entropy Alloys?

Photo by alice_photo - stock.adobe.com.

MAX-Phase Materials[10]: Somewhat influential

Influence mechanism
Extreme survivability in austere conditions makes MAX-phase materials reliably manufactured in bulk ideal for structural components of hypersonic glide vehicles operating in the thousands of Kelvin temperature range.

Rationale
Rated "somewhat influential" as they enable a small subset of nuclear weapons to be more effective but share characteristics with other classes of materials.

Outlook and indicators
Currently available in small quantities in specific laboratories, but no bulk manufacture of MAX-phase material, or MXenes, or widespread deployment in nuclear reactors.

Indicator(s):

1. Bulk manufacture of MAX-phase material (or MXenes).
2. Certified for use in nuclear reactors.

10 Structure and synthesis of MAX phase materials: a brief review; Revolutionizing Nanomaterials

Technological trends that directly influence the way in which future arms control agreements are monitored and verified

Metamaterials[11]: Very influential

Influence mechanism
Unprecedented lensing capabilities as a function of metamaterials that overcome the diffraction limit would provide monitoring and verification at high resolution from space (were it to become possible to build and deploy such a lens on a satellite), but may also inhibit those activities through perfect absorption, anti-reflection, or so-called cloaking.

Rationale
Rated "step-change" as bulk manufacture of metamaterials that overcome the diffraction limit remove a fundamental physical barrier to optical resolution.

Outlook and indicators
Already being prototyped for use in telescopes, metamaterials for enhancing the effectiveness of Earth imaging satellites are likely being developed in defence laboratories.

Indicator(s):

1. Metamaterials successfully deployed on telescopes, with particular focus on sub-10m mirror assemblies.

Digital Twins for Warhead Design and Optimisation[12]: Very influential

Influence mechanism
Digital twins could be used for front-end development of new weapons systems to rapidly reduce breakout times, with a very small footprint.

Rationale
Rated "very influential" as could lead to rapid development of proscribed systems under a future arms control agreement.

Outlook and indicators
Barriers to this technology being deployed are significant, requiring enormous computational resources, and technical expertise.

Indicator(s):

1. Digital twins commonplace in nuclear reactor operations

11 Metamaterial Tiles Boost Sensitivity of Large Telescopes; A hybrid invisibility cloak based on integration of transparent metasurfaces and zero-index materials
12 Digital Twins Facilitate Program Success for Sentinel

Additive Manufacturing[13]: Influential

Influence mechanism
Distributed manufacture of components for delivery systems may permit rapid mating of warhead and delivery vehicle if appropriate AM facilities are collocated with warheads.

Rationale
Rated "influential" as AM capable of producing a missile housing and engine, for example, introduces new uncertainties between adversaries regarding placement of delivery systems stipulated in future agreements.

Outlook and indicators
Already widely used in aerospace and beginning to be deployed in nuclear power contexts, matter of if, not when, it is integrated into nuclear weapons supply chains.

Indicator(s):
1. AM certified for the manufacture of critical nuclear reactor components, such as cladding and fuel pin assemblies.
2. Cases of export control breaches utilising AM occur and grow.

Autonomous Nuclear Reactors[14]: Influential

Influence mechanism
Loitering nuclear munitions, especially those undersea, may necessitate new arrangements if subject to arms control agreements.

Rationale
Rated "influential" as relevant for a subset of weapons and delivery systems.

Outlook and indicators
Multiple systems are already in the testing phase (Burevestnik, Poseidon), these systems may continue to propagate through nuclear arsenals.

Indicator(s):
1. Burevestnik testing outcomes improve
2. Burevestnik deployed

13 Dual-use distinguishability: How 3D-printing shapes the security dilemma for nuclear program
14 One nuclear-armed Poseidon torpedo could decimate a coastal city. Russia wants 30 of them

Technological trends that directly influence the conditions in which a future arms control agreement must be negotiated

Autonomous Computer Network Operations[15]: Step-change

Influence mechanism
Unprecedented volumes of cyberattacks via AI-enabled computer network operations could destabilise delicately balanced security relationships.

Rationale
Rated "step-change" because, as the Russia-Ukraine war demonstrated, CNOs take a long time to plan, and once they have been used up, the cadence at which they can be deployed is limited, which may not be the case with AI-enabled CNOs.

Outlook and indicators
Already in the testing phase in commercial contexts, the pace of advancement is unclear, but reasonable to assume this is a near-medium term reality.

Indicator(s):

1. DARPA's AIxCC Competition (semi-final and final at DEF CON 2024, and 2025 respectively).
2. Commercial availability of AI-enabled cybersecurity agents.

Generative AI - Media[16]: Step-change

Influence mechanism
Confidence in the veracity and providence of the media consumed by the general public may drop as deeply personalised media becomes the norm, driving growth in mistrust of traditional media outlets and governments.

Rationale
Rated "step-change" as the scale, pace, and quality of AI-generated content continues to advance exponentially.

Outlook and indicators
Genuine revolution in the consumption of media and narratives is imminent, shown by the advent of OpenAI's Sora, Google's Gemini etc.

Indicator(s):

1. AI-generated CGI used in films or video games would indicate that prompt engineering is sufficiently sophisticated to make the leap from storyboard to finished product.
2. Reputable media outlet issues an apology for running a story based on AI-generated narrative.

15 Cyber risks go beyond geopolitics; Identifying Key Relationships between Nation-State Cyberattacks and Geopolitical and Economic Factors: A Model; DARPA AI Cyber Challenge Aims to Secure Nation's Most Critical Software
16 How generative AI is boosting the spread of disinformation and propaganda

Room Temperature Superconductors[17]: Step-change

Influence mechanism
The LK99 ambient temperature superconducting false alarm showed how radically a (mechanically usable) room-temperature superconductor would be, revolutionising every aspect of physics, electrical and electronic engineering.

Rationale
Rated "Step -change" as how this technology is leveraged or controlled globally will have extreme consequences for geopolitics and global diplomatic relations.

Outlook and indicators
Achieving superconductivity at room temperature in laboratory conditions may be verging on impossible, and doing so with a mechanically usable material that can be manufactured in bulk even more so.

Indicator(s):
1. Researchers will have learned lessons from the LK99 debacle and will jealously guard advances until absolutely certain that the material is a RTSC, so monitoring of cutting edge literature is crucial.

Brain-Computer Interfaces[18]: Very influential

Influence mechanism
Trust in a world characterised by widespread usage of BCIs may be drastically reduced, and any state able to reliably implant such devices would have substantial leverage over others that cannot, not to mention the impact on global technological divides.

Rationale
Rated "very influential" as it may upend diplomatic activities as a function of reduced trust.

Outlook and indicators
The outlook is certainly dependent on the type and capabilities of the BCI of interest - wearables are likely medium term, but a ""neural lace"" is substantially further off.

Indicator(s):
1. Venture capital funding for BCIs jumps substantially from present.
2. Wearable BCI's for biomedical purposes certified by national health authorities.
3. Implanted BCI's for biomedical purposes certified by national health authorities.

Lethal Autonomous Weapons[19]: Very influential

Influence mechanism
Reliance on LAWs in a world where norms against their use have been eroded could entrench global divides, as states with LAWs can utilise them with great effect, with reduced human risk.

Rationale
Rated "very influential" as global dialogue on this subject is already fractured, and diplomatic concerns could increase in a world where access to such systems is distributed unevenly.

Outlook and indicators
The outlook is dependent upon the system in question and the development of an accepted definition of LAWs.

Indicator(s):
1. Definition of LAWs adopted.
2. Facial recognition enabled drones used in apprehension of criminals.
3. Drones monitoring public behaviour for criminal activity deployed in multiple major cities.

17 Room-temperature superconductors could revolutionize electronics
18 Progress in Brain Computer Interface: Challenges and Opportunities
19 The AI Military Race: Common Good Governance in the Age of Artificial Intelligence, Chapter 3: The dynamics of international diplomacy

Autonomous Nuclear Reactors[20]: Influential

Influence mechanism
Loitering nuclear munitions, especially those undersea, may drastically elevate tensions between states as detection would be extremely difficult, and verifying that a state's territorial waters are clear of such would be almost impossible.

Rationale
Rated "influential" as is only relevant for a small subset of weapons and delivery systems.

Outlook and indicators
Multiple systems are already in the testing phase (Burevestnik, Poseidon), these systems may continue to propagate through nuclear arsenals.

Indicator(s):
1. Burevestnik testing outcomes improve
2. Burevestnik deployed

Decision Support AI for Civil Purposes[21]: Influential

Influence mechanism
The use of AI-enabled policy advice, say in negotiations or crisis management, could be seen as disingenuous, or otherwise create new global divides and vulnerabilities.

Rationale
Rated "influential" due to the direct ethical and diplomatic concerns about using AI-enabled negotiating tools.

Outlook and indicators
Scale and use-case dependent, but likely a matter of when and not if, commercial applications will likely lead (civil) governmental applications, such as in negotiations, or as a central advice hub in a civil service department.

Indicator(s):
1. AI "board members" used in commercial contexts.
2. AI legal agents providing rapid legal advice to governments.
3. AI policy agents providing solutions and analysis for governmental departments.

Decision Support AI for Military Purposes[22]: Influential

Influence mechanism
The use of AI-enabled military advice from the operational to the strategic contexts could be seen as escalatory or cavalier, and also fuel global divides.

Rationale
Rated "influential" due to the direct ethical and equity concerns about the use of military AIs.

Outlook and indicators
Scale and use-case dependent, but likely a matter of when and not if, will be broadly paced by wider society's acceptance of AI-decision makers.

Indicator(s):
1. AI tactical advisors deployed in testing.
2. AI tactical advisors deployed in the field.
3. AI legal agents providing rapid legal advice to commanders.
4. AI agents providing solutions and analysis at the strategic or theatre level.

High Temperature Superconductors[23]: Influential

Influence mechanism
Reduced barriers to the use of quantum devices could have an important effect on global relations, but more impactful would be the medical uses for imaging, or reduced cooling load for magnetic confinement fusion reactors.

20 One nuclear-armed Poseidon torpedo could decimate a coastal city. Russia wants 30 of them
21 AI And The Future Of Government Artificial; intelligence will transform decision-making. Here's how
22 Algorithms of war: The use of artificial intelligence in decision making in armed conflict
23 The future of semiconductor procurement

Rationale
Rated "influential" as medical imaging is a need for many developing economies, as is the global drive for fusion power plants.

Outlook and indicators
Generally likely to follow previous trendlines and rates of change unless major new science or discovery emerges.

Indicator(s):
1. Monitoring of literature and plotting of trends in critical temperatures (at standard atmospheric pressure).

Biocompatible Materials[24]: Somewhat influential

Influence mechanism
Biocompatible materials and their applications for improving human health and cognition are liable to open up yet another global divide between haves and have nots and raises serious concerns about cybersecurity of implanted devices.

Rationale
Rated "somewhat influential" as the creation of global divides is not novel and the risks to global geopolitics and diplomacy remain low.

Outlook and indicators
Global health divides are already widening, and an uptick in bioengineered systems for medical purposes may accelerate that.

Indicator(s):
1. Number of biomedical engineering graduates increases.

Solid State Batteries[25]: Somewhat influential

Influence mechanism
The use of solid state batteries to make more efficient vehicles, drones, and energy storage would certainly be useful, but very much an incremental improvement.

Rationale
Rated "somewhat influential" as supply chain management and politics would be affected, especially between China and the US, two P5 countries.

Outlook and indicators
Recent laboratory developments at NASA suggest the technology is feasible, but rollout and refinement of use-cases dependent on industry appetite.

Indicator(s):
1. Structural batteries developed and deployed in UAVs

24 Engaging Biomedical Engineering in Health Disparities Challenges
25 The supply chain for electric car batteries is changing the world's geopolitics

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